

Final Report
STUDY METHODS TO STANDARDIZE
THERMOGRAPHY NDE

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ABSTRACT

The purpose of this work is to develop thermographic inspection methods and standards for use in evaluating structural composites and aerospace hardware. Qualification techniques and calibration methods are investigated to standardize the thermographic method for use in the field. Along with the inspections of test standards structural hardware, support hardware is designed and fabricated to aid in the thermographic process. Also, a standard operating procedure is developed for performing inspections with the Bales Thermal Image Processor (TIP).

Inspections are performed on a broad range of structural composites. These materials include graphite/epoxies, graphite/cyanide-ester, graphite/silicon-carbide, graphite phenolic and Kevlar/epoxy. Also metal honeycomb (titanium and aluminum faceplates over an aluminum honeycomb core) structures are investigated. Various structural shapes are investigated and the thickness of the structures vary from as few as 3 plies to as many as 80 plies.

Special emphasis is placed on characterizing defects in attachment holes and bondlines, in addition to those resulting from impact damage and the inclusion of foreign matter. Image processing through statistical analysis and digital filtering is investigated to enhance the quality and quantify the NDE thermal images when necessary.

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1.0 INTRODUCTION

Infrared thermography (IRT) has proven to be a valuable nondestructive evaluation (NDE) method for locating manufacturing and service related defects in advanced composite structures. Manufacturing defects such as contamination from foreign material or ply misalignment and service related impact damage producing delaminations or fiber breakage are just some of the potential candidates for detection by IRT methods. The primary advantage of using IRT as a NDE tool for assessing the structural quality is that large regions can be covered in a single operation, or pass. The IRT method is also non-intrusive, requiring no direct contact with the structure under test and can often be performed with little structural disassembly. The downside of IRT inspections is that the results are often very subjective, varying between test conductors and with application procedures. The purpose of this study will be to develop standardized thermographic procedures for evaluating typical aerospace structures.

Thermographic NDE techniques allow subsurface abnormalities to be visually detected by means of variations in surface temperature arising from the internal distortion of an injected heat field, such as from a flash lamp, or from within the structure as a result of rubbing, such as from a fatigue process. Measured “at distance”, IRT requiring no direct contact with the structure and can be produced over relatively large surface areas. Generally speaking, the limitation on the size of the area to be tested varies only with the size of the defect to be located and the geometry of the structure. The temperature variations are often very small, requiring specialized highly sensitive detection systems to locate small material abnormalities.

The purpose of this project is to develop new and innovative methods for modeling, acquiring and analyzing thermographic data, so that standardized test procedures can be developed and quantitative nondestructive measurements can be made of composite structures in near real time. Emphasis is to be placed upon constructing certification standards in the form of physical hardware and analytical models to make IRT more

applicable to testing the next generation launch vehicles and other aerospace hardware.

Recent advancements in digital thermal imagery along with the increase in personal computer computational power have brought thermography into the forefront of NDE as a viable approach for locating defects or other material abnormalities in aerospace structures. Thermography has been used to qualitatively detect subsurface corrosion in the wing skins of aircraft, locate delaminations and disbonds in honeycomb and foam core composite panels and find cracks in thin aluminum sheet. A major problem with thermography though, has been the lack of standardization, repeatability, practical modeling techniques and quantitative results.

Several factors have a significant effect on the detectability of thermography including size and depth of the flaw, local emissivity, environmental stability, material thermal conductivity and diffusivity, heating cycle, detector resolution, etc. By understanding the relationships between these variables the limitations of the IRT system to evaluate a given structure can be addressed and the proper procedures put in place to help optimize the resolution of the thermal measurement.

Advances in image processing through the use of digital filtering, time-temperature transient analysis and statistical methods should permit quantitative measures of the thermography data. Features within the thermal image obscured by background noise may be enhanced with these mathematical techniques providing valuable information on the integrity of the component under test.

The goal for this task is to develop thermographic inspection methods and standards for use in evaluating structural composites and aerospace hardware. Qualification techniques and calibration methods will be investigated to standardize the thermographic method for use in the field. Special emphasis will be place on characterizing defects in attachment holes and bondlines, in addition to those resulting from impact damage and the inclusion of foreign matter. Image processing through statistical analysis and digital filtering will

be investigated to enhance the quality and quantify the NDE thermal images.

Fourteen inspections are covered in this report. These inspections cover a broad range of structural composites. The structures range from simple plate test samples and standards to large “flight similar” parts. The thickness of the composites range from just a few plies to almost a hundred. Materials including graphite, Kevlar, titanium and aluminum are inspected with resins ranging from epoxies, cyanide-esters, silicon-carbides, and phenolics. Several structures with foam cores are also inspected.

In addition to reporting on inspections and their limitations, the plans for several pieces of hardware developed to enhance the thermographic inspections are given. Also, a standard operating procedure for the Bales TIP, flash unit and high intensity quartz lamps are given.

2.0 HEAT LAMP DESIGN AND CONSTRUCTION

A 1000 watt infra-red heat lamp was constructed (Figures 1 through 4) for use during thermographic inspections. The lamp was designed to provide a uniform heat source over an area measuring approximately 20 by 8 inches. The unit operates from a 208 VAC single phase power source. Heat is produced by a 1000 watt high intensity infra-red quartz lamp. The lamp housing is protected from the heat and energy is reflected to the test article by way of a highly polished parabolic stainless steel mirror.

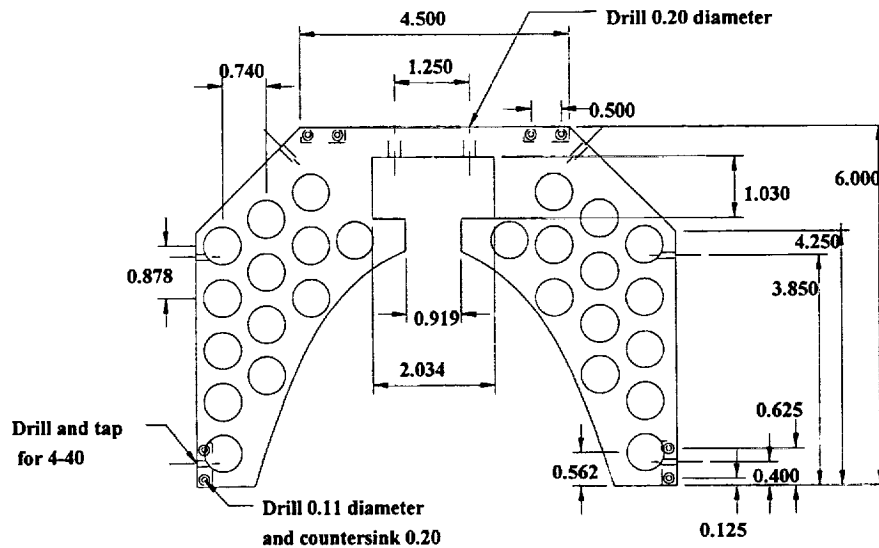


Figure 1. Lamp housing endplate.

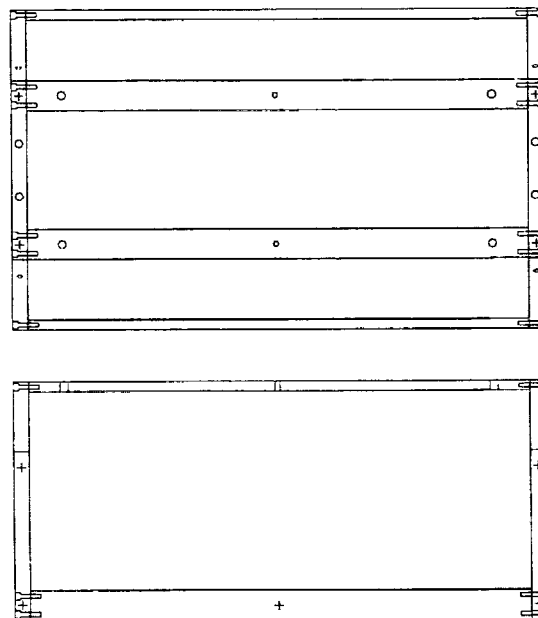


Figure 2. Lamp Frame

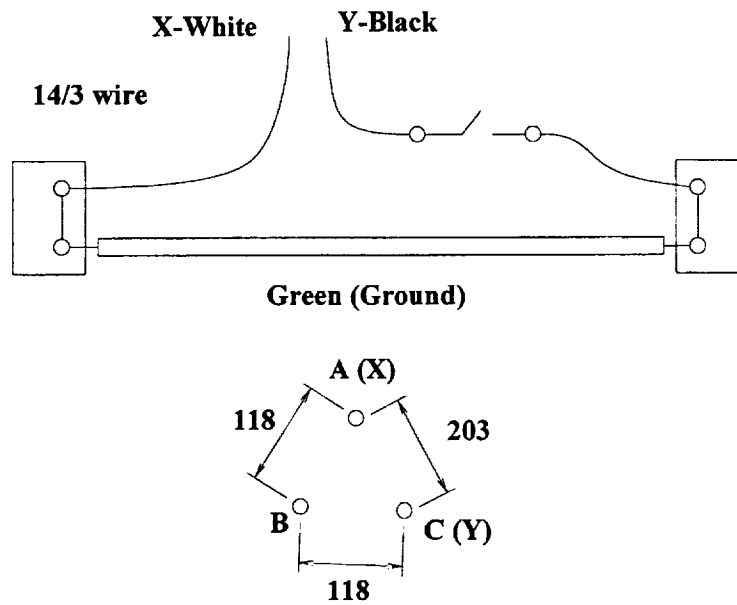


Figure 3. Wiring diagram for heat lamp.

Part Number	Vendor	Description	Quantity	Price
A	UAH	End Plate	2	N/A
B	UAH	Stringer	4	N/A
C	UAH	Side Cover	2	N/A
D	UAH	Top Cover	1	N/A
3566	Home Depot	Handle	2	8.59
3439	Builders Square	30 A Switch	1	10.90
N/A	UAH	14 gauge Wire	3 ft	N/A
N/A	UAH	Wire end	5	N/A
ALI-8617-02	G.E. Supply	Lamp base	2	9.02
5V223	Grainger	Lamp	1	39.99
9953	Builders Square	14-3 Power cord	20 ft	14.20
N/A	Stock	Power plug	1	N/A

Figure 4. Parts list for heat lamp.

3.0 STANDARD OPERATING PROCEDURE FOR THERMOGRAPHIC INSPECTIONS

The major safety requirements and procedural steps necessary to perform a thermographic inspection using the Bales TIP and either flash or slow heating. These procedures are intended as a supplement to the Bales TIP reference manual, providing a concise operations guide. Those personnel unfamiliar with the system described should read and understand the entire inspection process and procedure Before attempting to perform a inspection. For detailed operating and diagnostic procedures, consult the Bales TIP reference manual.

3.1 THE BALES THERMAL IMAGE PROCESSOR

3.1.1 Safety

3.1.1.1 Quartz halogen bulbs are used in the flash unit and heat lamp. These bulbs generate a tremendous amount of light and heat when in operation. Never look directly at the bulb when it is powered and never touch the bulb with your bare hand, whether or not the bulb is lit. Any oils or contaminants from your hand may create an abnormally hot spot on the bulb which may result in bulb failure and potential fracture.

3.1.1.2 Always make sure all power switches are in the off position before plugging either the flash unit, heat lamp or thermal camera system into their appropriate power sources.

3.1.1.3 Never place combustible materials in front of the flash unit or heat lamp.

3.1.1.4 Never disconnect or handle the main power cord to the flash unit (The large diameter cable running to the pulse forming network [PFN]) unless the PFN has been discharged, the main power switches are in the off position and the high voltage power supply is disconnected from the 110 VAC source. The main power cord carries up to 1600 volts at all times that the unit is charged.

3.1.1.5 Always shut down the computer system by either selecting QUIT from within the program menu or typing shutdown from the Bales prompt (text mode).

3.1.1.6 Set the lamp on its handles to cool down after use. This will help to prevent overheating of the electronics inside the lamp housing. Once the lamp has cooled, turn the lamp so that the reflector faces down to protect the bulb.

3.1.1.7 Never turn the power on to the flash unit until the imager software is running. Also never turn off the imager until the flash unit has been discharged.

3.1.2 Operation of the Bales imager system

Ensure that the system is configured as shown in Figure 5.

Turn on main power switch on the pulse conditioning unit (PCU).

Once the system boots up, type after username; TIP200.

The main window should show up on the screen. Click on the green menu box (upper left hand corner of screen) to display the on-screen menu.

Click on the SYS command button to open the System setup window.

Click on Optics Set-up to initialize system.

Once Optics Status reads Good then click on Done to exit window.

From the on-screen menu click the SCAN button to initialize the imager.

From the on-screen menu click on the COLOR MAP button.

Set the Sensitivity to 0.05 (C/level and the # Of Levels to 80 (or whatever value is appropriate for the test at hand) by moving the slide bar with the center mouse button. You can also move the slide bar by clicking to one side of the button with the mouse.

Set the extended colormap to REPEAT ALL.

From the on-screen menu click on the FOCUS button. Set the focus by either selecting Autofocus or by adjusting the focus slide bar with the mouse.

From the on-screen menu click on the G2 button. This will take you to the acquisition menu.

To acquire a thermal image; first select Fast Scan Image [New]. An image box will appear in the live scan frame. To move the box, click on its upper left corner with the Left mouse key and then drag it into position. To adjust the size of the box, drag the lower left hand corner of the image box with the Left mouse key. Once you have determined the correct image box, select it by clicking inside the box with the Middle mouse key.

A separate image box will now appear in the center of the screen. Move it to the lower left hand side of the screen by grabbing it by the top left hand corner with the Left mouse key and sliding it down and to the left. Once in place release the Left mouse key. Select the image window with the center mouse key to make it active.

From the G2 window select Fast Scan Image [Collect]. The system will ask which image

to scan; select the image box created in step 15 by placing the white circle mouse pointer in the image box and clicking on the center mouse key.

Once the image box is selected, set the number of images to the maximum available and the time per frame to an appropriate value. Typically the time per frame is set to 20 msec for flash heating and between 0.5 to 1 sec per frame for hand held lamp or heat gun heating.

Apply heat (Section 1.3 or 1.4) and press OK to begin acquisition.

Once the image sequence is collected it can be stored to the hard drive using the SAVE button found on the on-screen menu. Note: The mouse pointer must be inside the subject I.D. box to assign a name to the output file. Select ONE IMAGE to save an image sequence. Place the white dot mouse pointer on the image sequence to save and click the center mouse key. Select start and end frame to save and then click on OK.

When finished with the thermal inspection, click on the red X button in the upper left hand corner of the image box to clear the image and data buffer. Repeat inspection process as required.

To exit the program, click on the red QUIT button in the upper left hand corner of the screen. Once the operating system indicates it is safe to shutdown, turn off the main power at the PCU.

3.1.3 Flash Heating

Do not turn on the power to the flash system until reaching step 8 of the previous procedure. The flash system is triggered from the imager software and will fire "Flash" on its own if the imager software is not enabled.

Ensure that the flash unit is configured as shown in Figure 6.

Proceed to step 17 of Section 1.2. (Do not select OK to acquire image as this will initiate the flash unit.)

Set the Remote/Local Switch on the back of the High Voltage Power Supply (HVPS) to Local.

Make sure the main power and high voltage switch are off on the HVPS. Set the voltage potentiometer to 7 (1.4 kvolt) and the current potentiometer to 5 (250 milliamp).

Make sure the DUMP switch is off on the Pulse Forming Network Unit.

Turn the main power switch on and after a few seconds or once you hear a low click, switch the high voltage power on.

The meter should read 1400 volts and less than 20 milliamp when the flash unit is fully charged.

Continue setting up the imager software as described in the proceeding section.

The flash will be very hot and bright. Announce to those individuals in the same room as the flash unit that you are about to fire the flash unit, and to look away from the unit. Do not put any combustibles directly in front of the flash unit, including yourself.

When the OK button is pressed the imager will fire the flash unit, collect the thermal sequence and begin recharging the capacitor bank in the pulse forming network.

To discharge the flash system, turn off the high voltage switch and flash the lamps. After the flash, flip the DUMP switch to on and wait until the voltage level is at or below 10 volts. When that level is reached it is safe to turn off the main power and if desired shut down the imager.

Note: If the imager is shut down before the flash unit is discharged

the flash unit will fire on its own.

3.2 Heating by way of the 1000W infrared heat lamp

Make sure the power switch on the top of the heat lamp is in the off position.

Make sure that the bulb and reflector area are clean and free any debris that could catch on fire. If the bulb is contaminated clean with alcohol and a soft, clean, lint free rag and let dry for several minutes. Never touch the bulb with your bare hand or any source that could leave a residue.

Plug the lamp into a single phase 208 VAC source.

Grasp the lamp by both handles and hold it in a horizontal position with the reflector facing away from yourself and any other personnel in the room. (The lamp may be operated vertically for short periods of time, but horizontal scanning is recommended for maximum bulb life.)

Make a practice pass with the lamp to ensure that your will not strike the test article or be obstructed in any way. The lamp should be held approximately 1 to 2 inches from the test surface as it is slowly scanned over the test surface. The rate of movement will depend upon the thickness and or thermal mass of the part. For example, a thick part will need to be scanned slower than a thin part. Never stop at any one place for more than a few seconds.

After the part has been heated, turn the lamp off and set the aside to cool down. It is best to set the lamp on its handles with the reflector facing up to prevent overheating of the electronics inside the lamp as the bulb cools. Once the lamp is cooled, flip it back over to protect the bulb.

3.3 Helpful hints on operating the Bales TIP software

3.3.1 To print a *.TIF Image

Select PRINT from the on-screen menu.

Select DOSS TIFF and PORTRAIT.

Define a filename, such as b:filename.tif.

Select ONE IMAGE. A white icon mouse pointer will appear. Place it in a corner of the image you wish to print and click the center mouse key.

3.3.2 To recall a saved image

From the main menu select RECALL.

Select FIRST TEN to display the first ten images on the storage disk.

Once you have found the image you want, select that image filename and click on RECALL.

3.3.3 To sequence through image frames

1. Left mouse key on green number block to move forward one frame at a time
2. Right mouse key on green number block to move backward one frame at a time
3. Center mouse key on green number block to auto-sequence through images

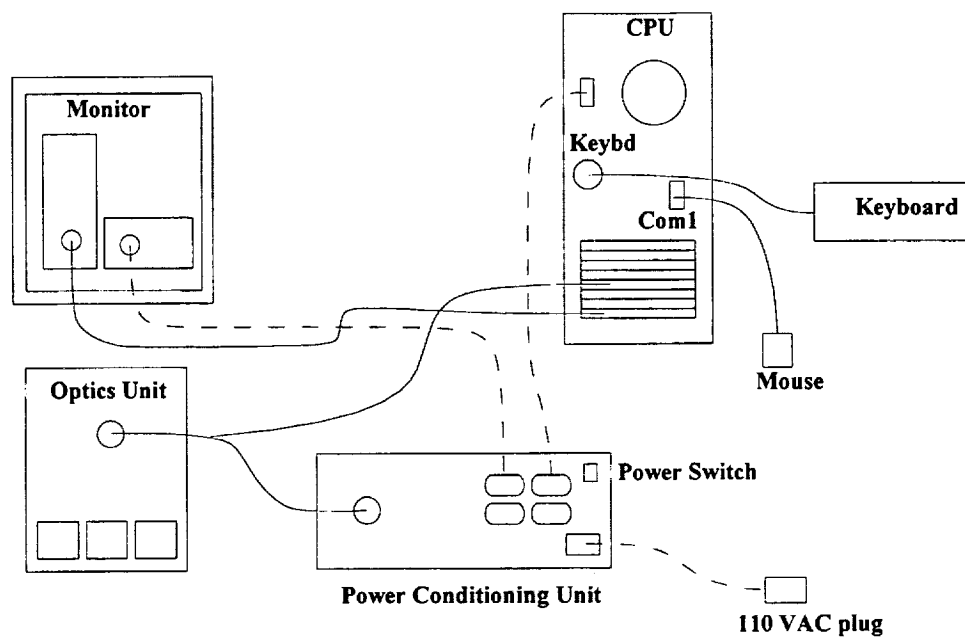


Figure 5. TIP System

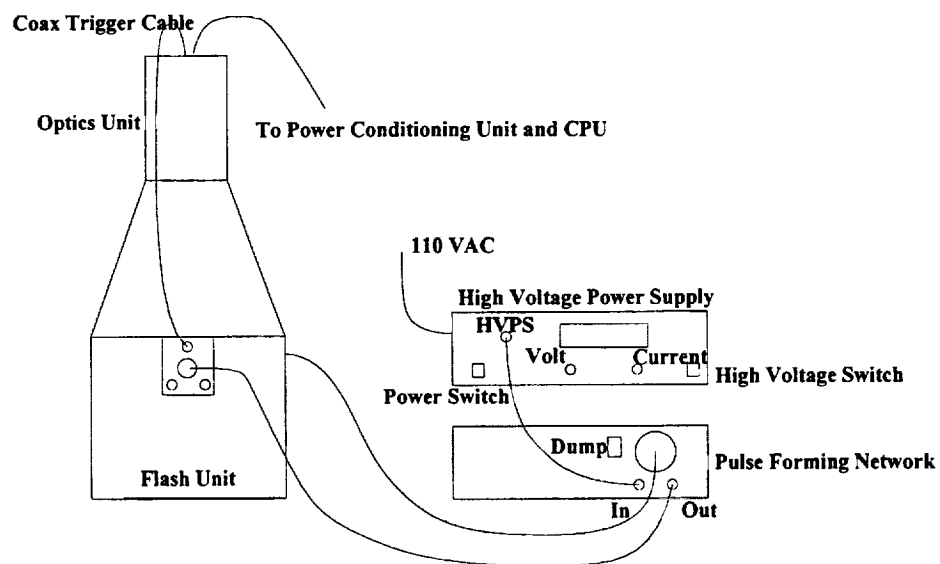


Figure 6. Flash System

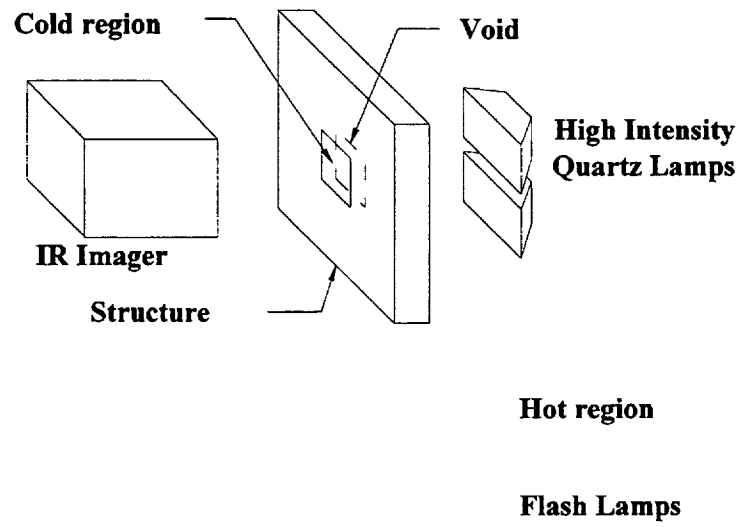


Figure 7. Back side heating and front side viewing

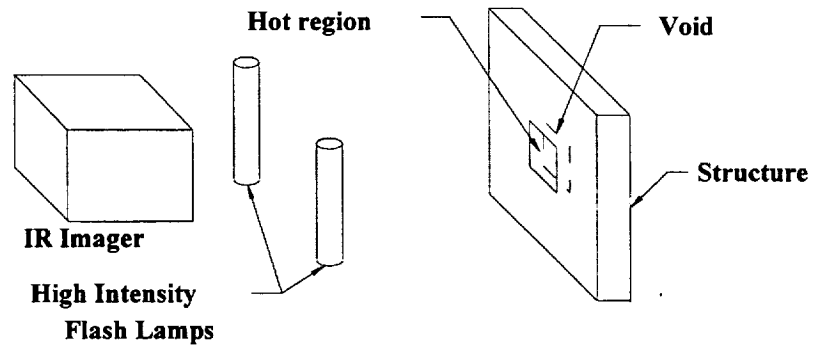


Figure 8. Front side heating and viewing

4.0 SUPPORT HARDWARE FOR THERMOGRAPHIC INSPECTIONS

4.1 Bales imager tripod yoke

The Bales imager tripod yoke was constructed to allow the camera to be used without the somewhat restrictive mount that is part of the original system. The yoke was fabricated from 3/16 aluminum plate.

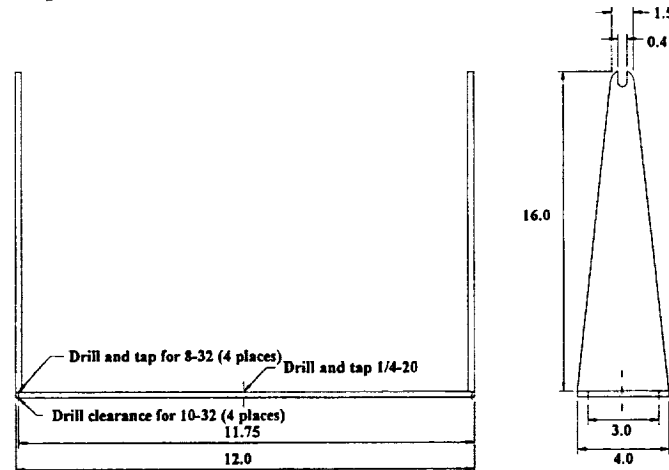


Figure 9. Tripod Yoke.

4.2 Bales flash unit tripod mount

A "T" shaped tripod mount for the Bales flash unit was constructed to permit inspections of large structures. The hood is supported at its balance point, with or without the extension cap, through bolted connections on either end of the main flash box.



Figure 10. System configuration.

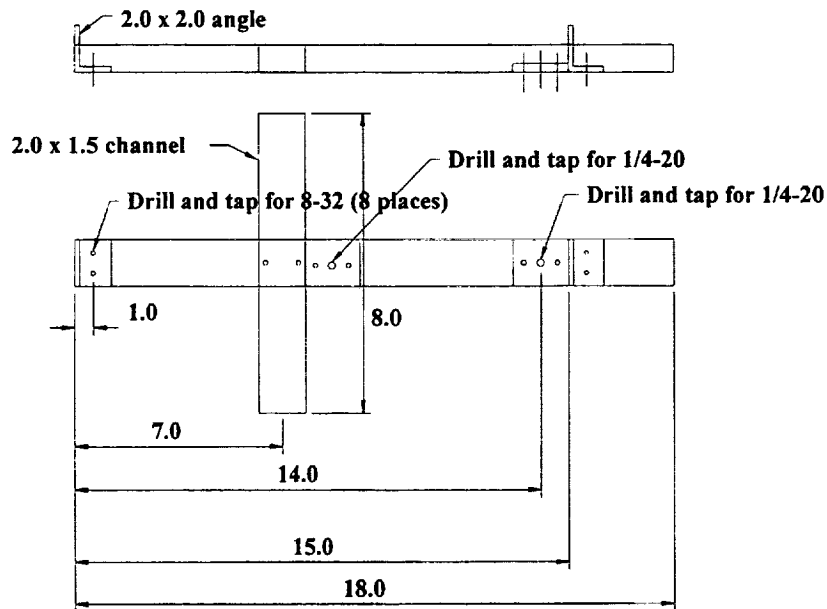


Figure 11. Hood tripod mount.

4.3 Amber control pad umbilical

A 300 foot extension to the control pad was fabricated for the Amber Radiance 1 camera. The extension was sized to allow control of the camera from a safe distance when monitoring structures in a hostile environment, such as the test area at MSFC.

The existing cabling system was altered so that the control pad could be used with either the existing short cable or with the addition of the extension. The diameter of the wire in the extension cable was chosen based upon maintaining an equivalent resistance to that of the commercially available 20 foot extension cable.

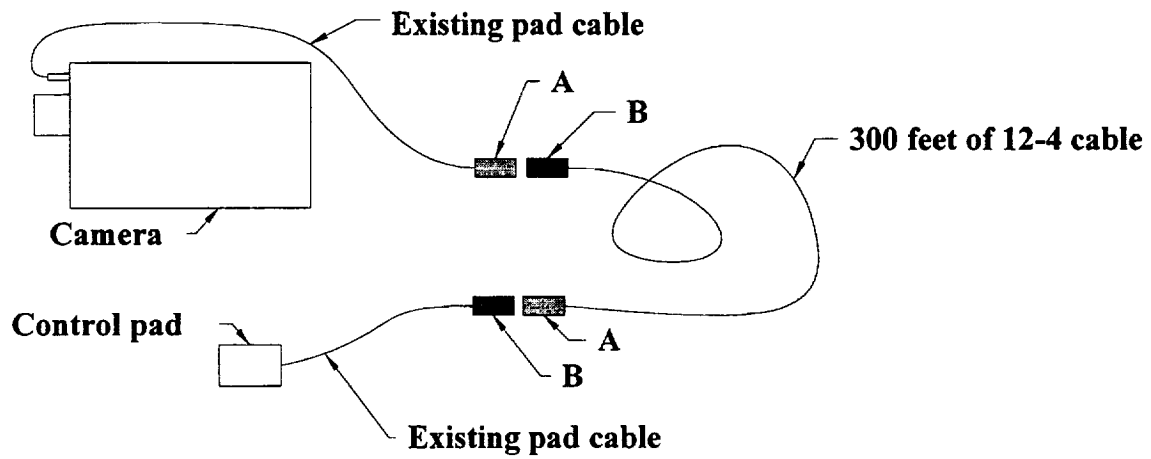
Resistance "R" = Density "ρ" * Length "L" / Area "A")

$$R = \rho * L / \pi * \text{Diameter}^2 \text{ "D"}^2$$

$$\therefore L(20\text{ft}) / D^2(26 \text{ AWG}) = L(300\text{ft}) / D^2$$

$$20 / (0.01594)^2 = 300 / D^2 \quad \text{therefore the required diameter is at least } 0.04365 \text{ inch.}$$

12 AWG wire has a diameter of 0.080808 inch.



A = Male 4 pin Amphenol connector
B = Female 4 socket Amphenol connector

Wiring Schematic for Amber 300 foot umbilical

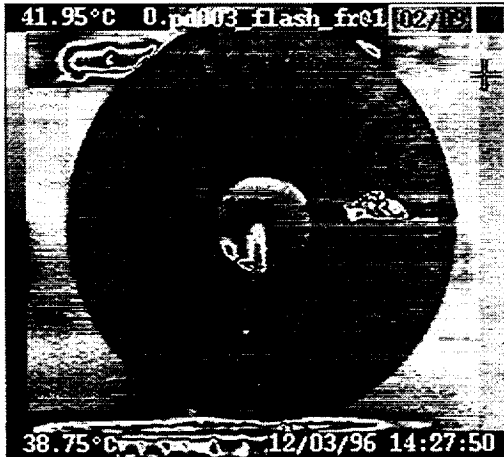
Figure 12. Amber umbilical.

5.0 THERMOGRAPHIC INSPECTION RESULTS

5.1 Carbon/Silicon carbide blisks

Both sides of the disks were inspected with the Bales TIP system using front face (camera side) pulse heating at a distance of 32 inches. The pulse amplitude was set at 1400 volts and the image processor configured to scan with a 20 msec per frame delay.

No thermal abnormalities were detected.



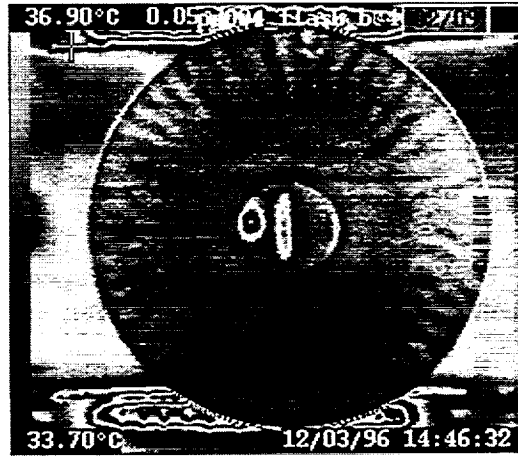
Disk 0180-02-003 (Front)



Disk 0180-02-003 (Back)

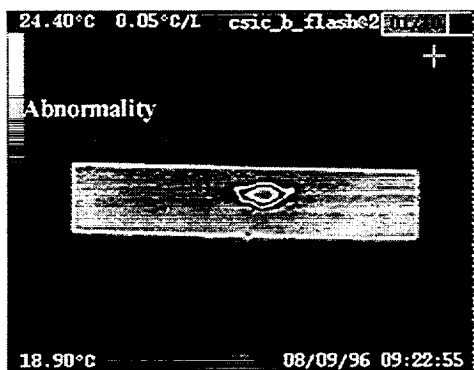


Disk 0180-02-003 (Front)

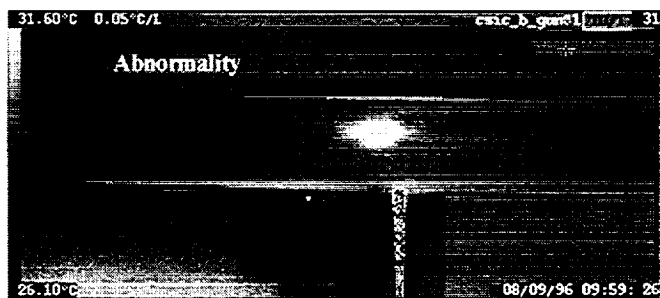


Disk 0180-02-004 (Back)

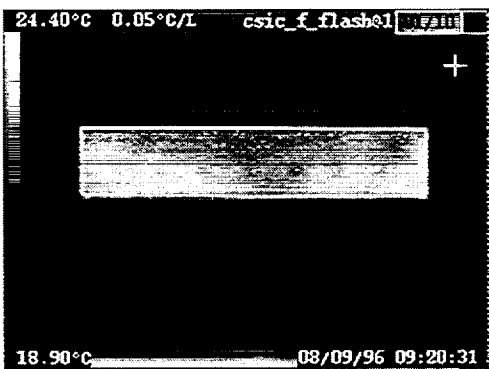
To determine the depth to which the thermographic inspections were penetrating the blisks, a 5.5 by 0.5 by 0.25 inch carbon/silicon-carbide bar was supplied for use as a thermographic defect standard. The bar was inspected using both flash and slow heating before any planned defects were added to determine the initial quality of the bar. As shown in the following figures a large abnormality was found on one face of the bar. It appears that this region is resin starved and may therefore have high porosity.



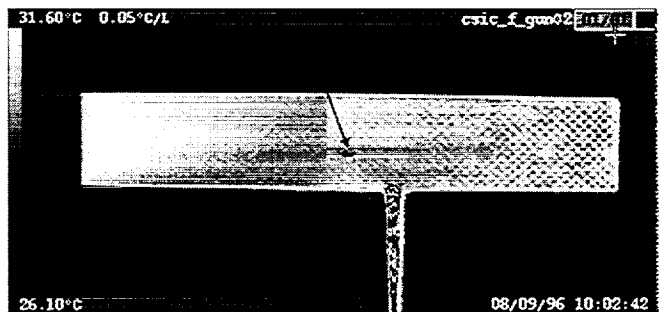
Back/Flash heating



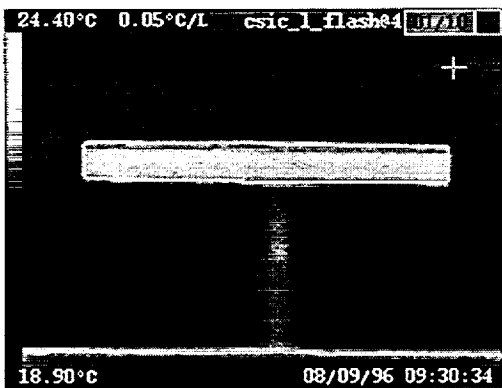
Back/Heat gun



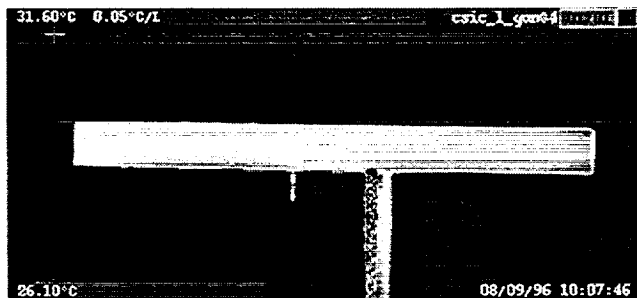
Front/Flash heating



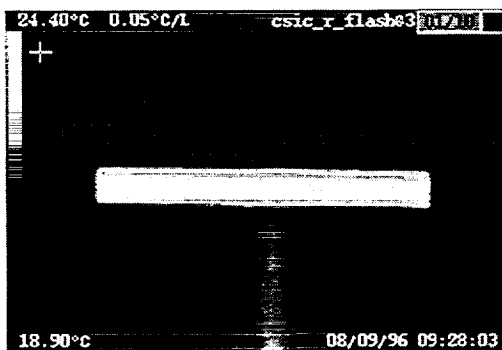
Front/Heat gun



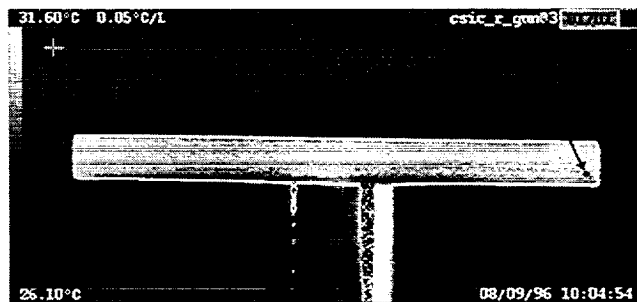
Left/Flash heating



Left/Heat gun

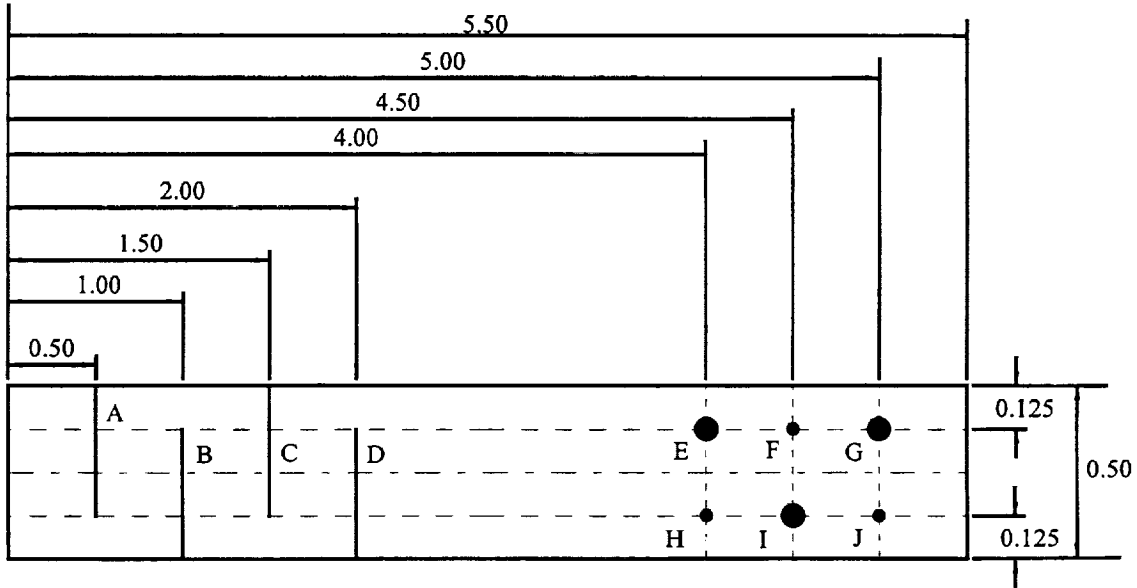


Right/Flash heating



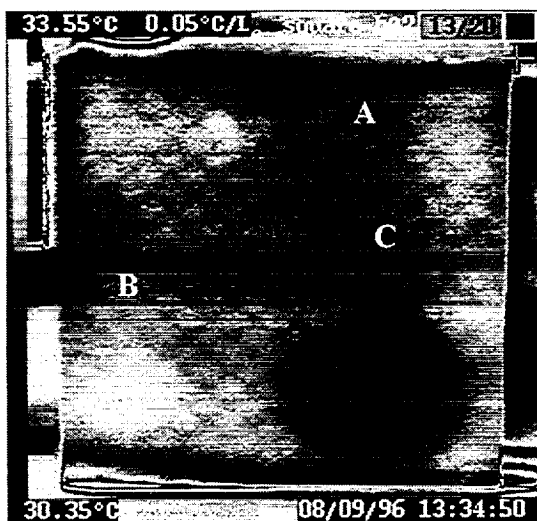
Right/Heat gun

Defects were manufactured by drilling flat bottom holes through to specified depths as shown in the following figure. None of these planned defects were detected using either flash or slow heating. More work will need to be done with the carbon/silicon-carbide material to determine the sensitivity of thermography to detecting defects in that material.

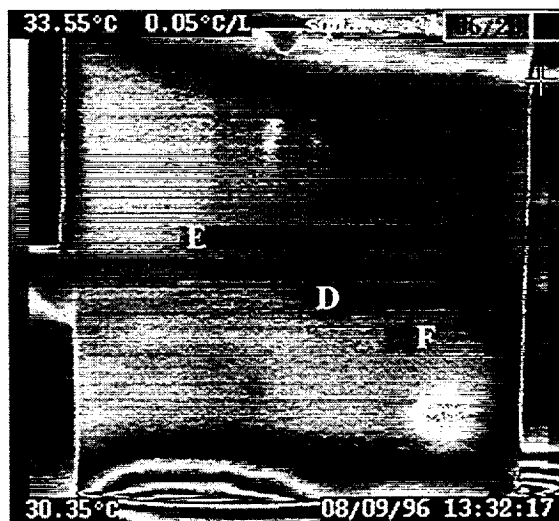


Item	% thickness location	Description
A	25	drill 1/16 inch
B	25	drill 1/16 inch
C	50	drill 1/8 inch
D	50	drill 1/8 inch
E	25	1/8 inch flat bottom hole (FBH)
F	75	1/16 inch FBH
G	50	1/8 inch FBH
H	25	1/16 inch FBH
I	75	1/8 inch FBH
J	50	1/16 inch FBH

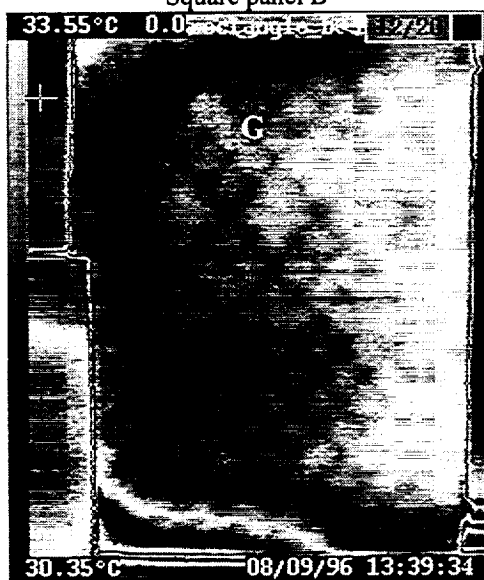
5.2 Titanium/Aluminum Panels



Square panel B



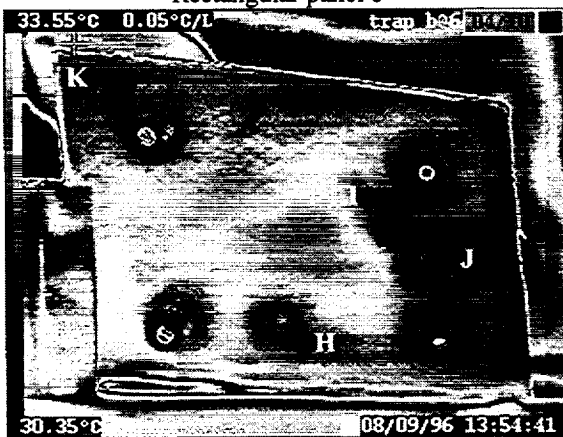
Square panel A



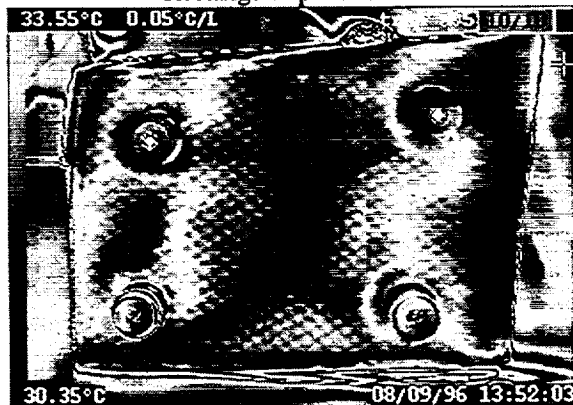
Rectangular panel b



Rectangular panel B



Trapezoidal panel B



Trapezoidal panel A

5.3 Thermography of Solid Rocket Motor (SRM) Nozzle

Erosion problems in the throat region of the Graphite/Phenolic SRM nozzle lead to an NDE investigation into possible low density zones. Two nozzle segments were supplied for examination with possible low density regions.

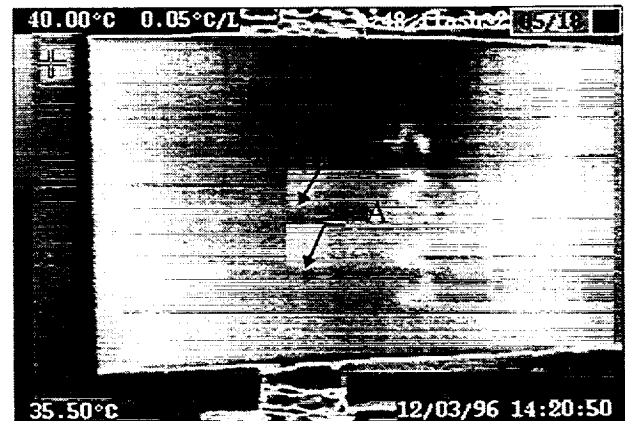
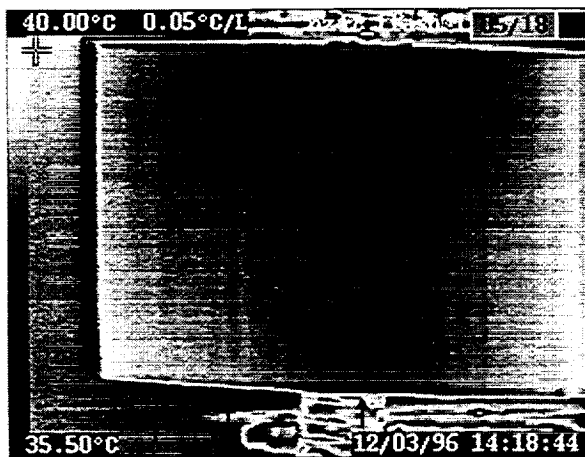
The nozzle was examined utilizing the Bales TIP system configured for both flash and manual heating. During flash heating (1500v) the nozzle segment was viewed from the heated side at a distance of 32 inches with a delay time of 20 msec per frame. During manual heating a hot air gun was used and the imager to part distance set to 16 inches. The delay time for manual heating was set to 0.5 sec.

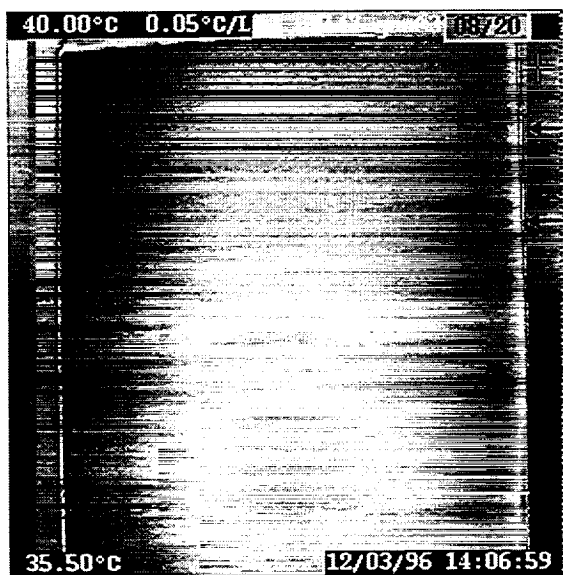
Indications: SN47

Several bands are visible across nozzle, three of which are indicated on thermograms. The bands persist for approximately 20 frames and are still evident after removing a portion of the rough surface.

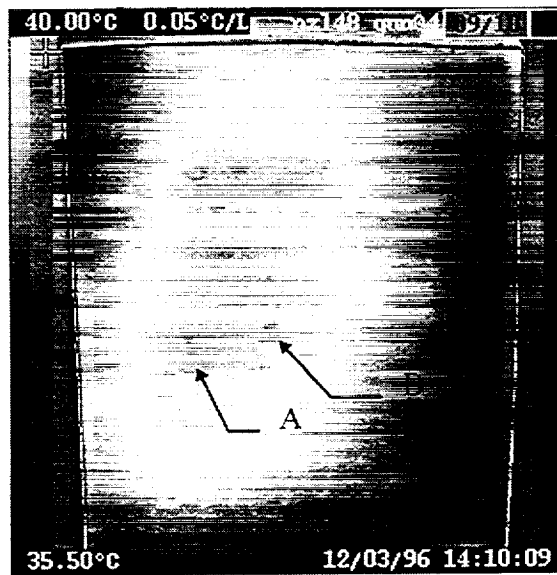
Indications: SN48

Several small thermal abnormalities are evident early in image sequence; two are labeled on thermograms. These abnormalities fade after just a few frames indicating that they are at or very close to surface.

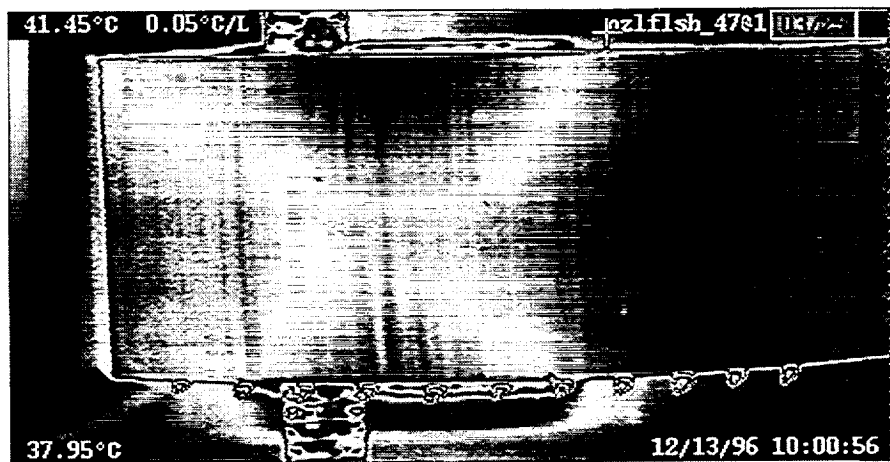




SN47 Heat gun



SN48 Heat gun

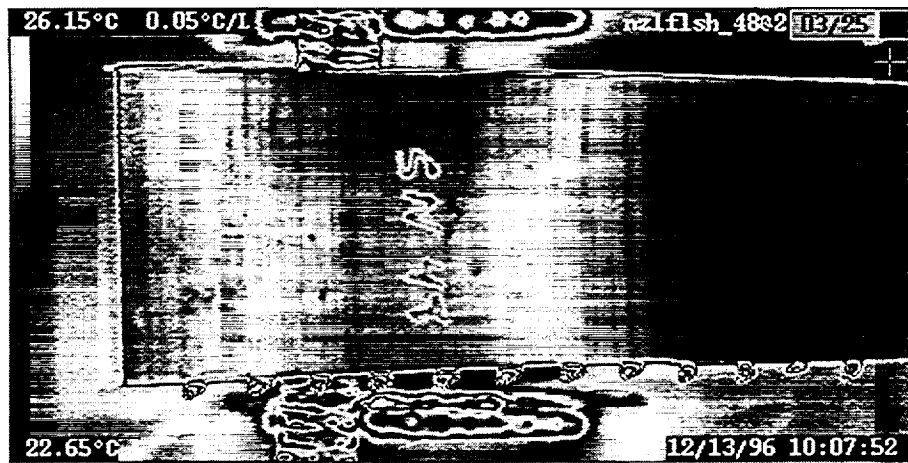


Nozzle 47 (80 msec after flash)

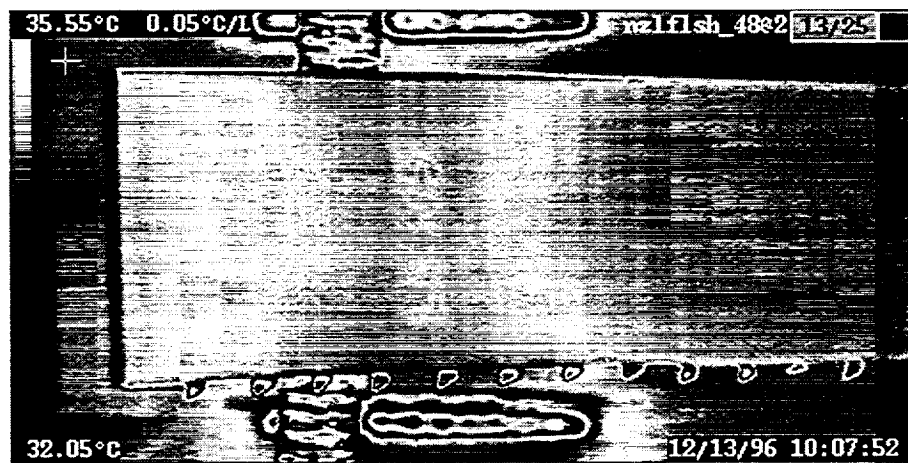


Nozzle 47 (280 msec after flash)

Note: Tick marks at one inch interval.



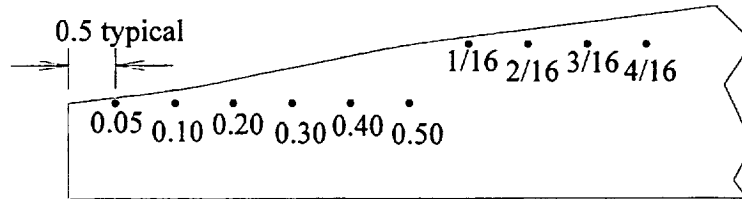
Nozzle 48 (80 msec after flash)



Nozzle 48 (280 msec after flash)

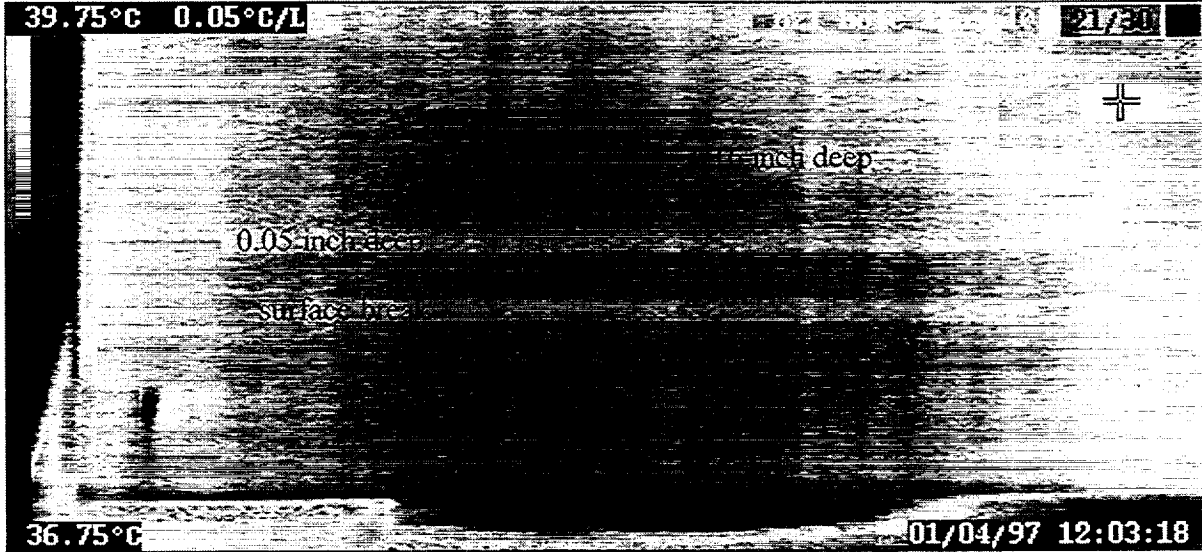
Note: Tick marks at one inch interval.

To determine how deep the thermographic inspection was penetrating into the nozzle a series of holes were drilled into the side of Nozzle Segment SN 47. Ten holes, 1/16 inch diameter, were drilled parallel with surface, approximately 1 1/4 inch deep. The holes were drilled 1/2 inch apart at depths of "0.1, 0.2, 0.3, 0.4, 0.5", "1/16, 1/8, 3/16 and 1/4" of an inch from surface.



Flash heating (1500v) from front (viewing) side of part was used to thermally excite the nozzle segment. As with the unaltered nozzle the imager was set with a 20 msec per frame delay and viewed from 32 inches.

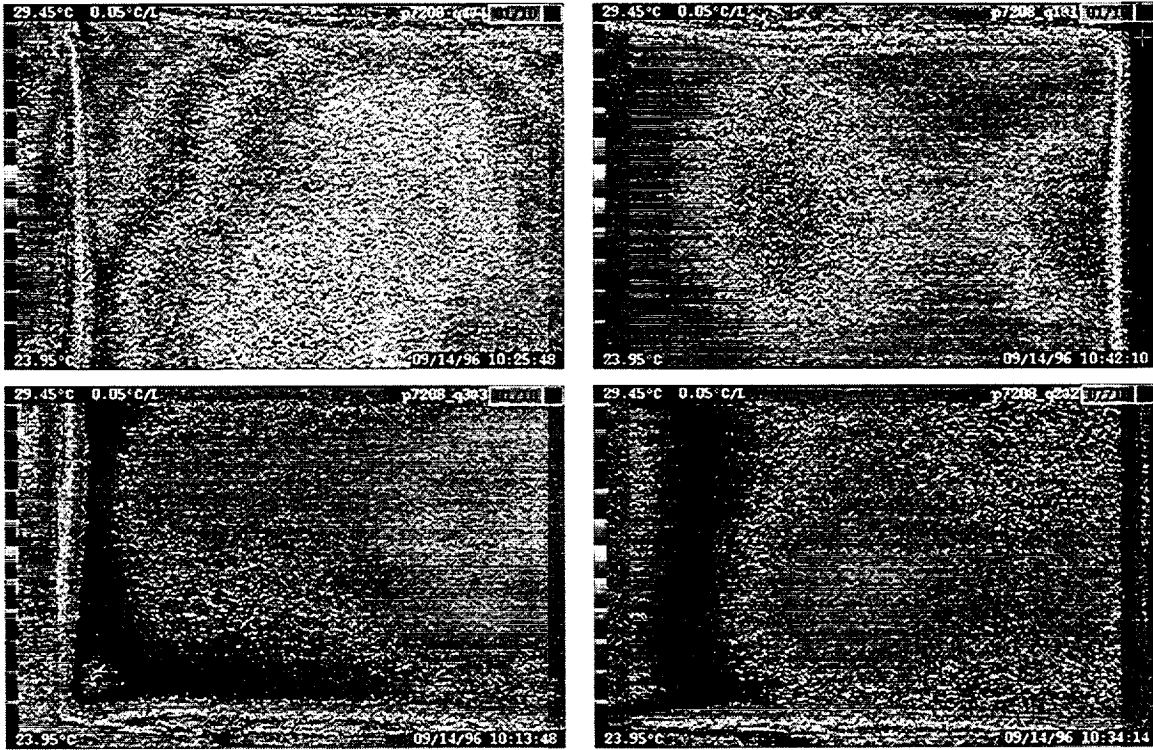
The only holes which were visible were 1/16 and 0.05 inch below the surface. Since the primary defects of interest were over 1/4 inch deep thermography was ruled out as a viable technique for the inspection of the nozzle segments.



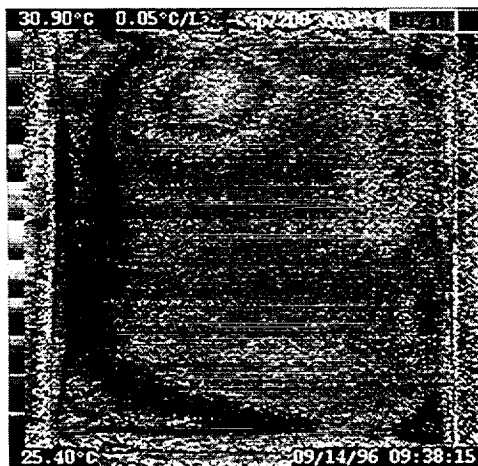
5.4 Graphite/Cyanide-ester Panels

Three Graphite/Cyanide-Ester tensile test panels were inspected for the X-33 project. The panels were all heated from the back surface with 2 - 500 W quartz heat lamps. The frame delay for each inspection was set to 0.5 sec per frame and the camera to part distance for full view set to 70" and 30" for section views. In all cases no thermal abnormalities detected.

5.4.1 Panel 7208

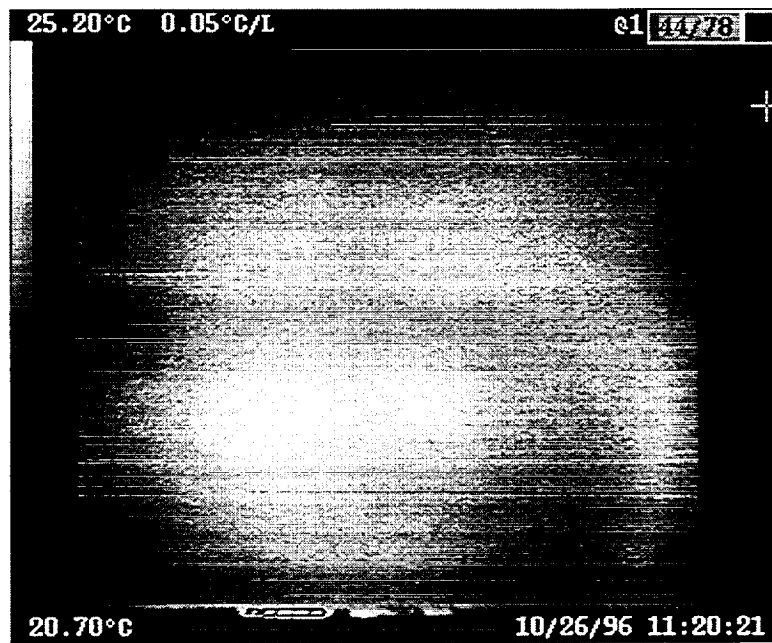


Quadrant Views (4 ft camera to panel)

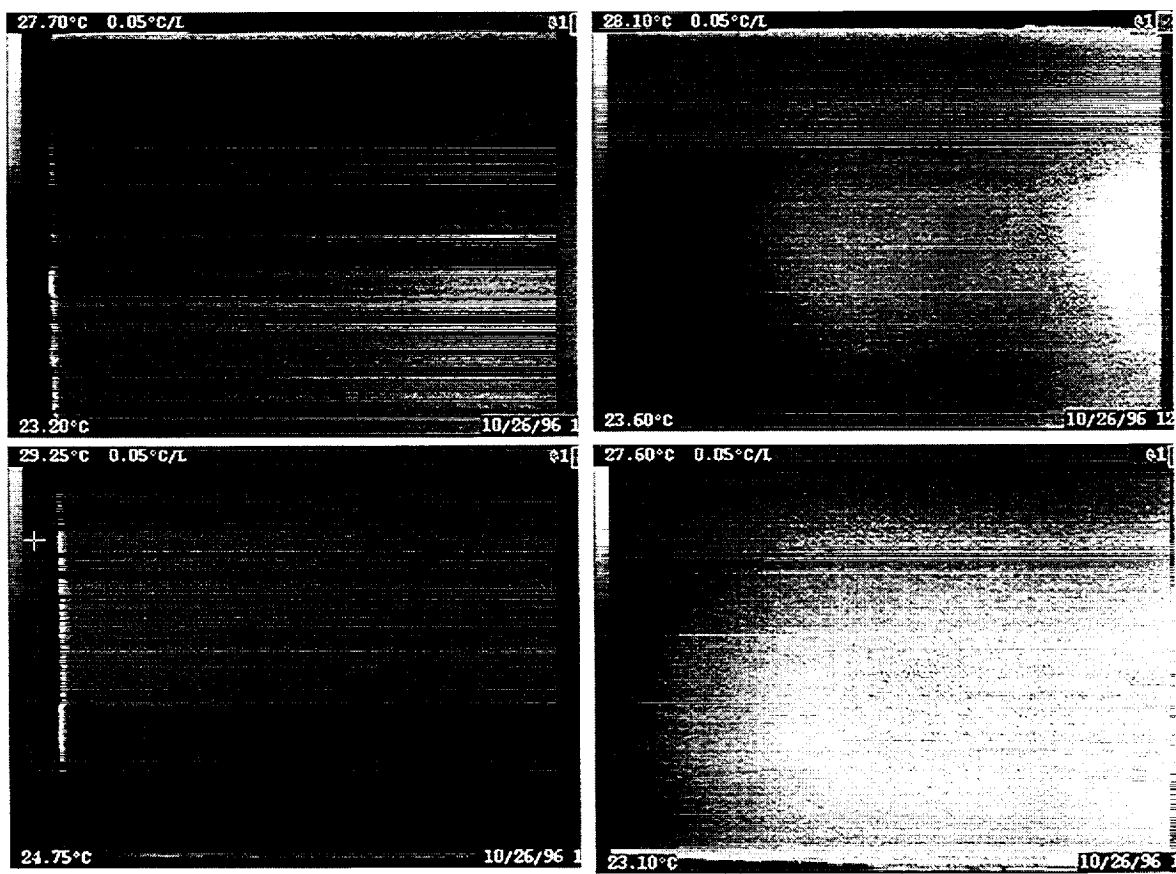


Full view (8 ft camera to panel)

5.4.2 Panel 7210 (40" by 34")



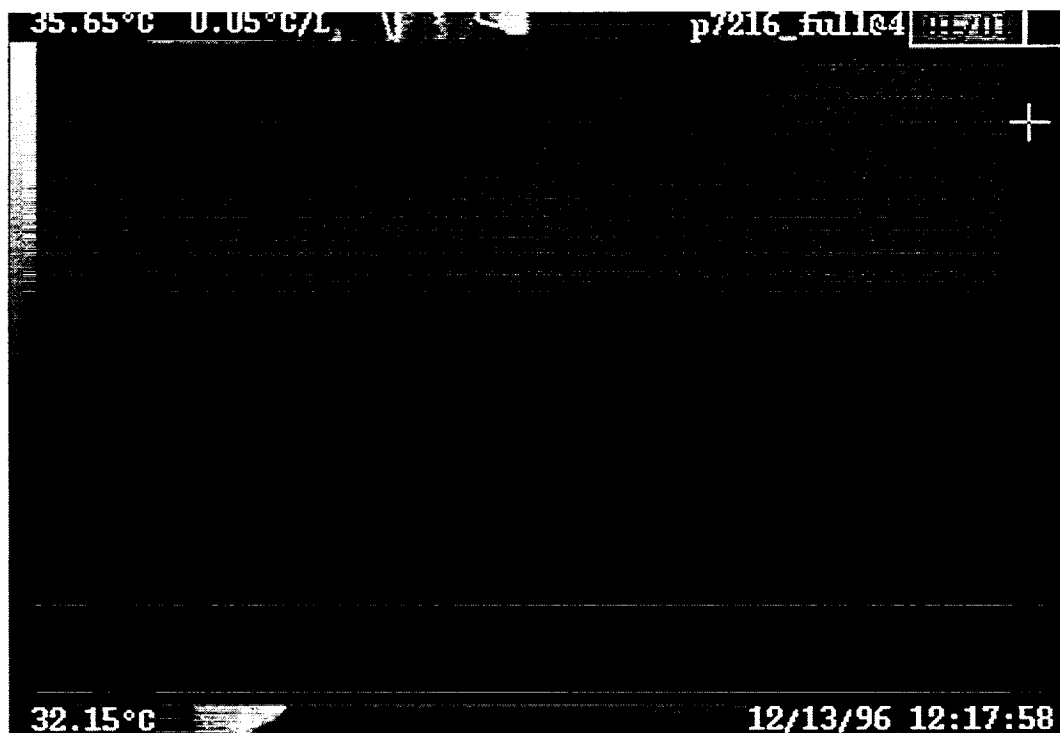
Full view (8 ft camera to panel)



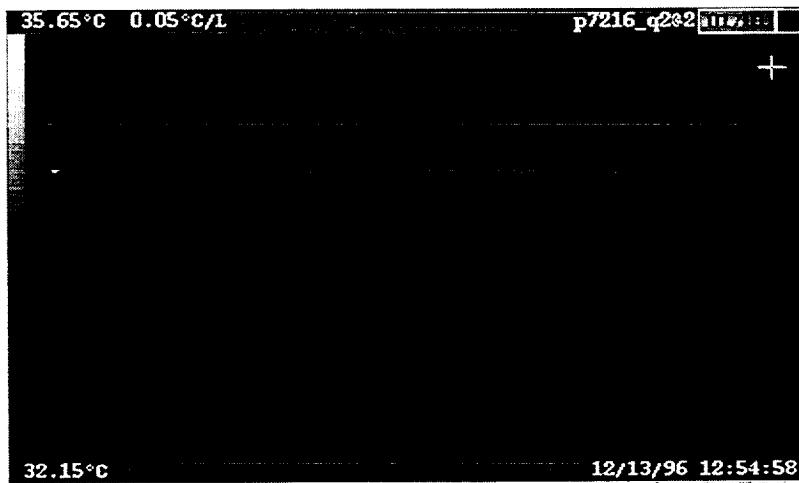
Quadrant view (4 ft camera to panel)

5.4.3 Panel 7216

TOP



(24"x36")
BOTTOM



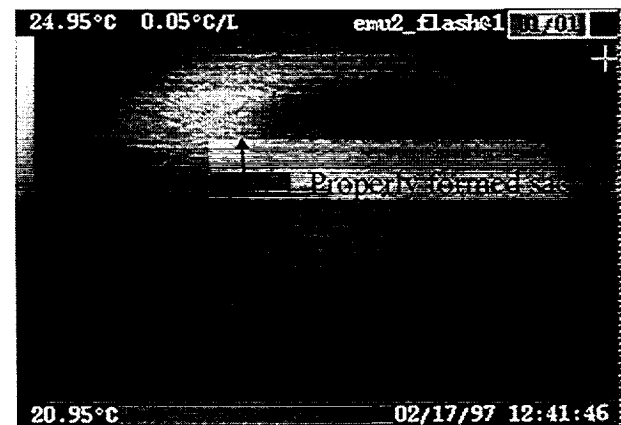
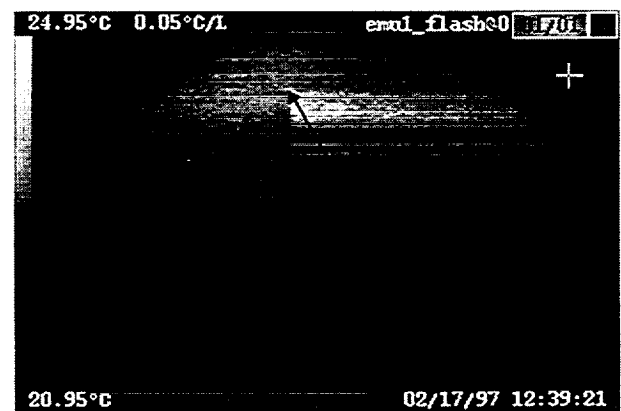
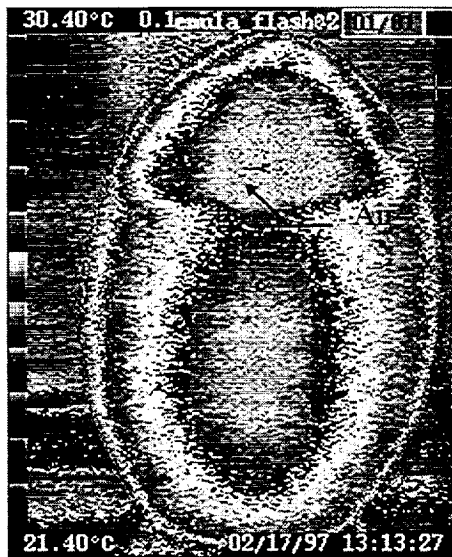
B
O
T
T
O
M

T
O
P

5.5 EMU Eggs

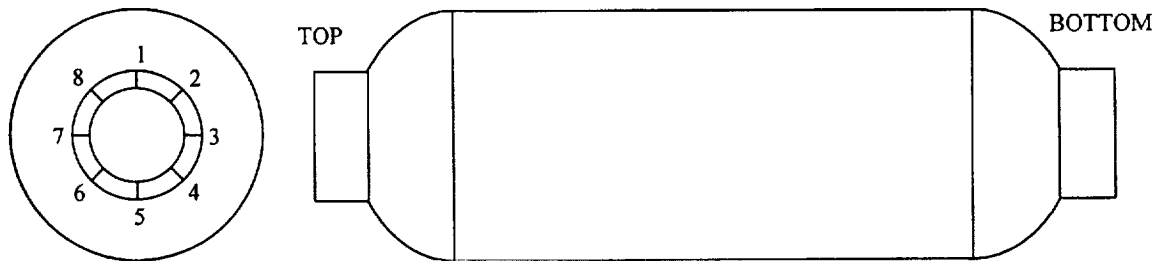
The thermographic evaluation of Emu eggs indicated that it was possible to detect the presence of a torn air bladder. The eggs were inspected utilizing flash heating (1400v) at a distance of 16 inches with a 20 msec per frame delay.

In order to determine if the sack was torn or in place the egg was imaged on its side and on end. As seen in the first set of images, the air pocket moves indicating that the sack is ruptured. On the other hand, the second set of images show that the sack remains in position as the egg is turned.



5.6 Graphite/epoxy pressure vessel

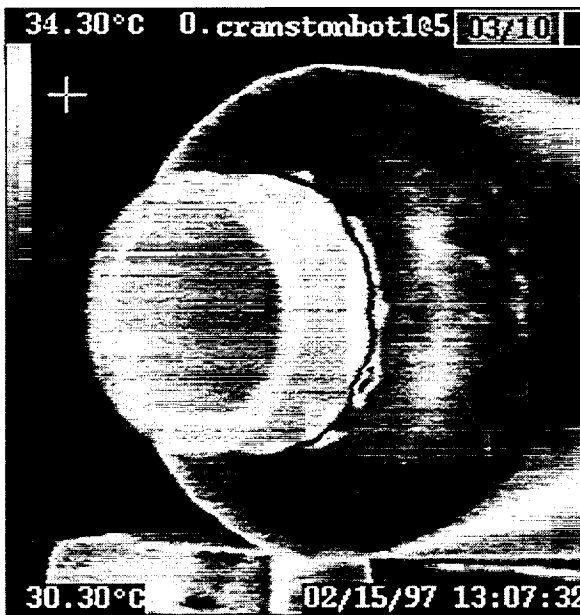
An eighteen inch tall, six inch diameter graphite/epoxy pressure vessel was inspected for manufacturing defects using the Bales TIP. The vessel was formed by filament winding over a foam core and aluminum shell. Of particular interest was the location of disbonds between the graphite shell and aluminum inner liner. Also due to the potential for impact damage during the removal of the urethane foam core, location of any delaminations in the graphite skin were of interest. The vessel was imaged at 32 inches using flash heating (1400v) with a 20 msec per frame delay.



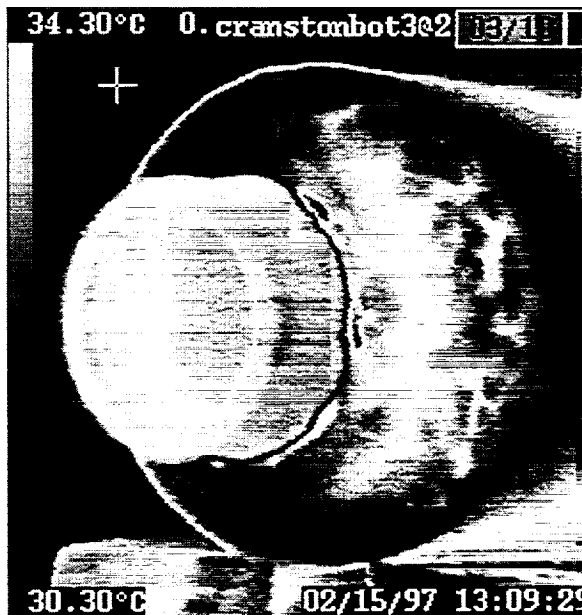
The thermal indications in the hoop region of the side views indicates some possible scattered disbonding of the gr/ep shell from the inner liner. Small hot patches can be seen in each of the side view images. The hot regions would indicate an area where heat from the flash unit was trapped on the surface by a insulating air pocket “disbond” below it. These indications tend to be in the quarter inch square size range. More severe thermal indications are present in the transition region between the hoop and dome. A band of disbonds appears to wrap all the way around the vessel. Some of these transition region abnormalities grow into the hoop and dome region, in the wind direction, which is typical of delamination/disbond growth in filament wound structures.

The end and quarter end views of the vessel shows the same sort of thermal abnormalities as the side views. Small hot regions of potential disbonded shell can be seen to extend all the way around the end of the vessel.

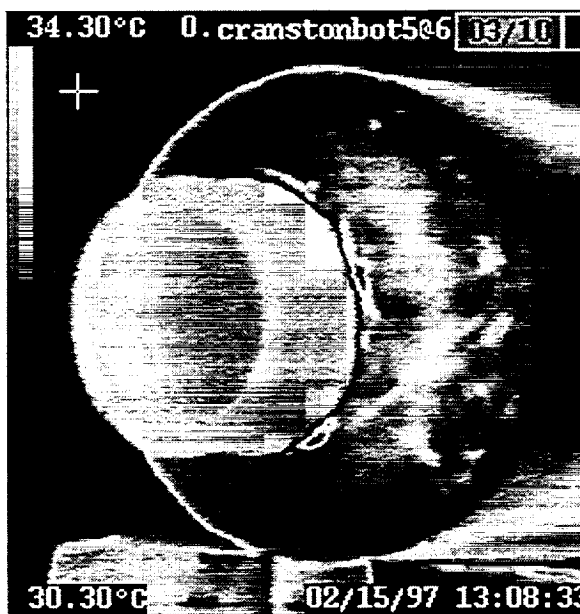
It should be noted that these some of the thermal abnormalities shown may be due to sources other than disbonds, such as resin rich/starved regions, nonuniformity of the inner liner or porosity in the shell itself. To confirm the source of the thermal abnormality a vessel would need to be thermally inspected then dissected.



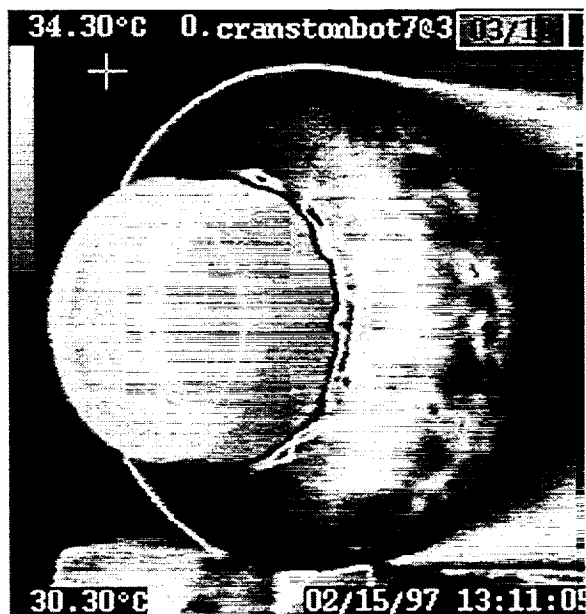
Bottom 1



Bottom 3



Bottom 5



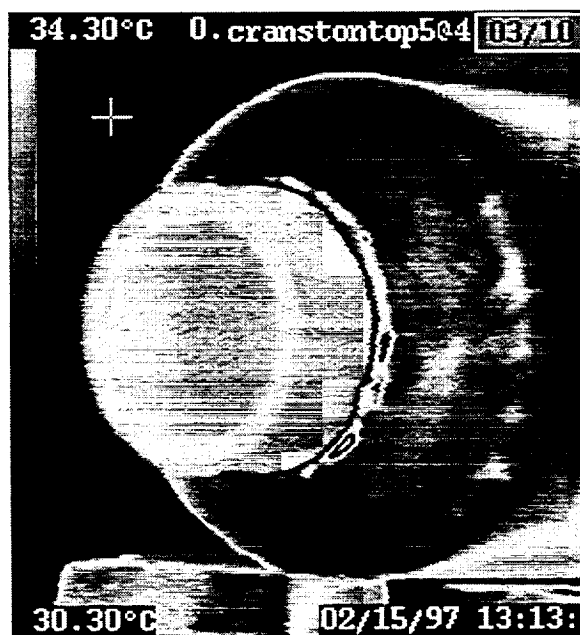
Bottom 7



Top 1



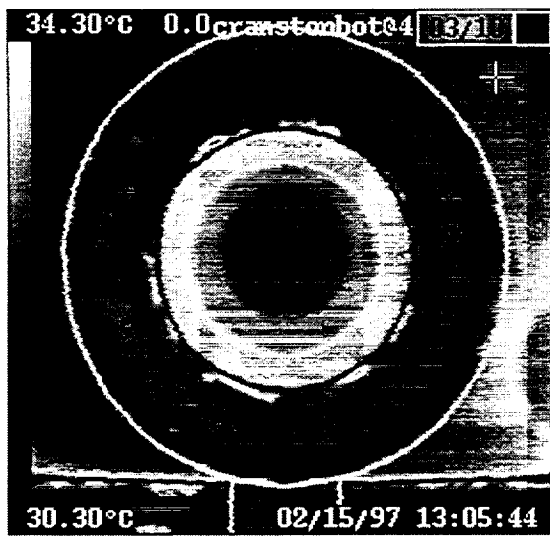
Top 3



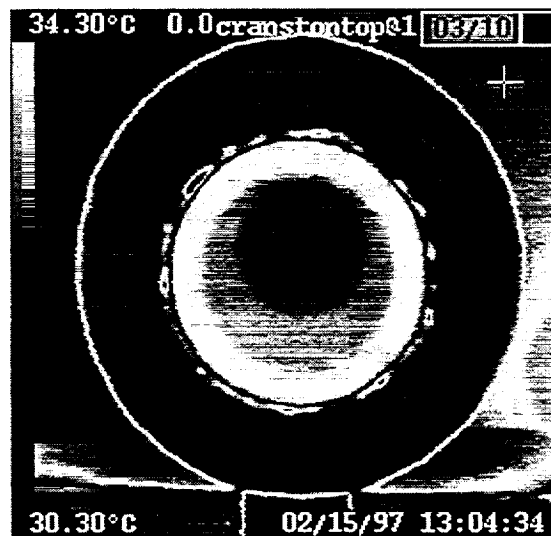
Top 5



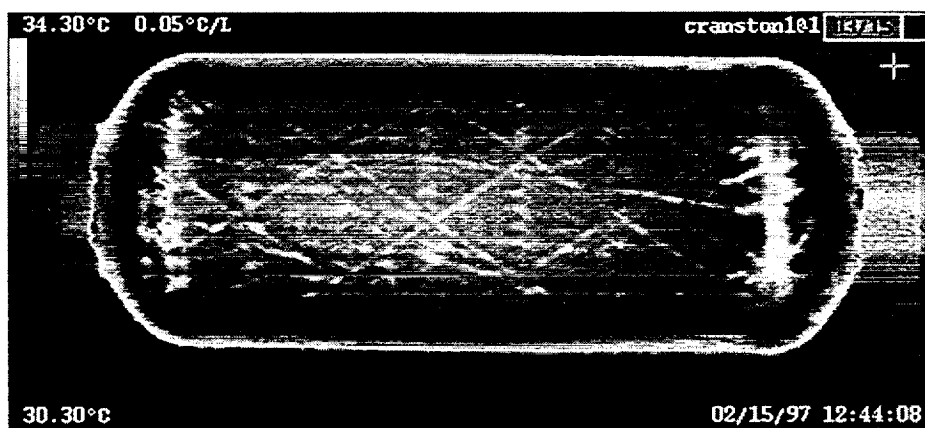
Top 7



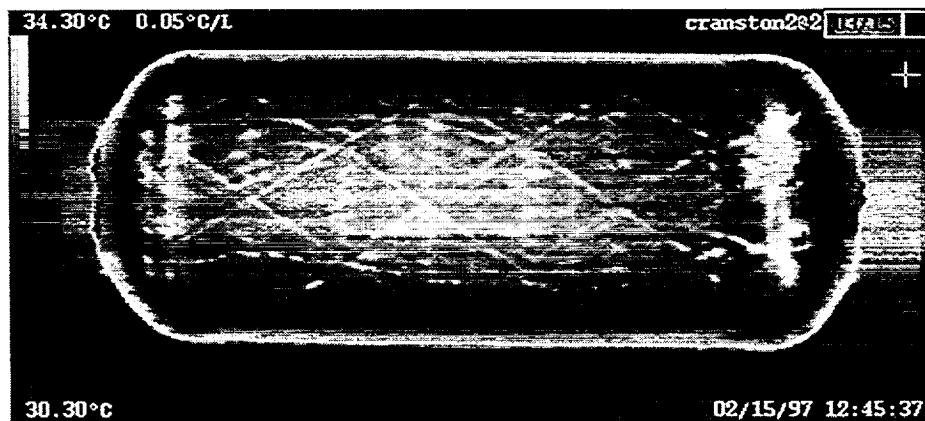
Bottom



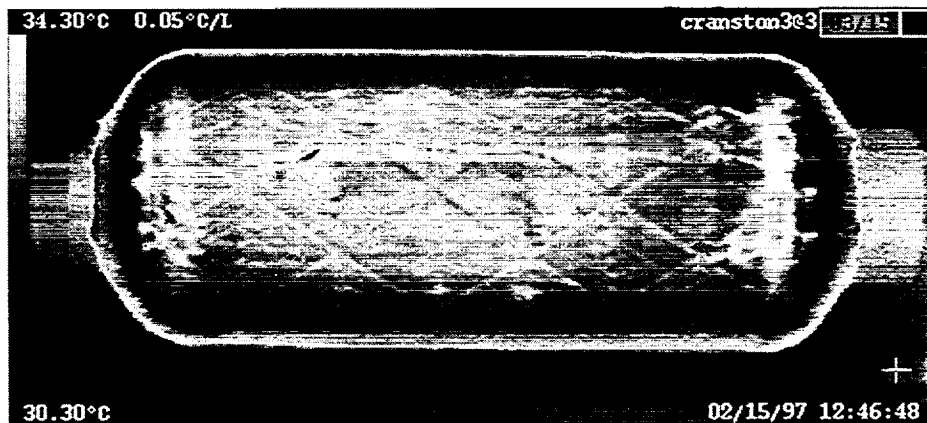
Top



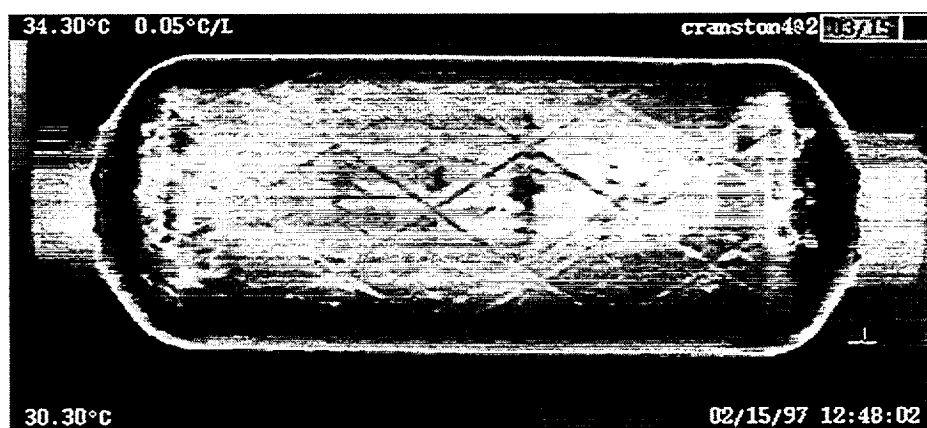
Position 1



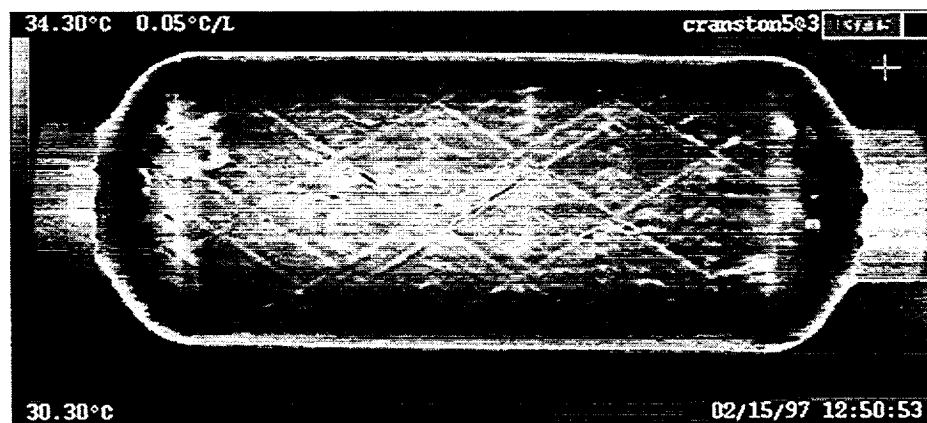
Position 2



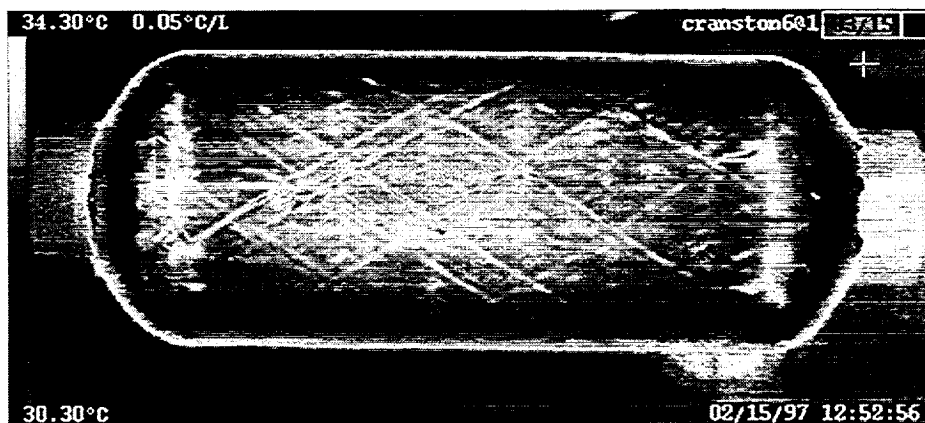
Position 3



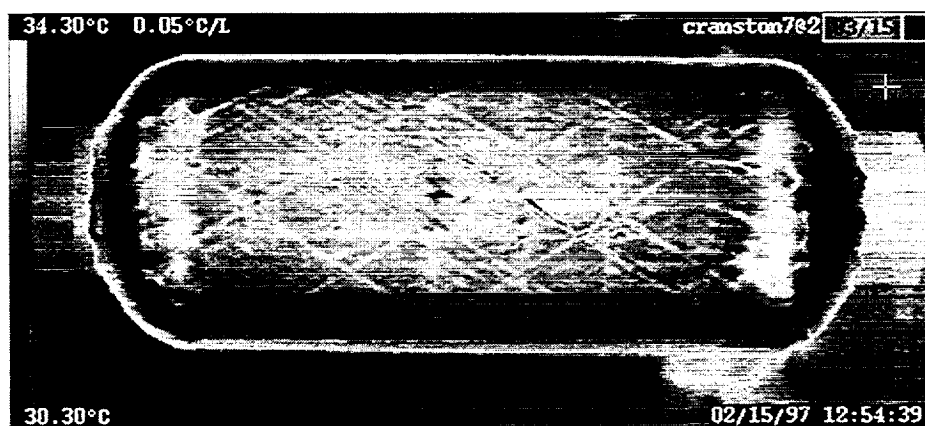
Position 4



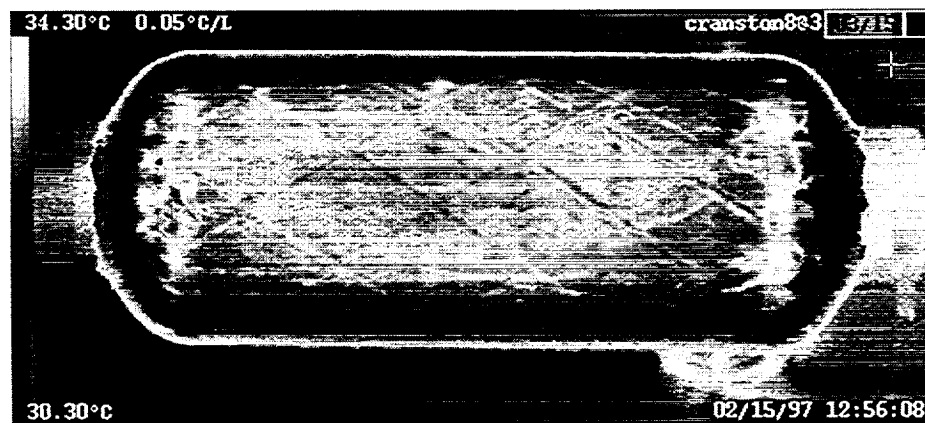
Position 5



Position 6

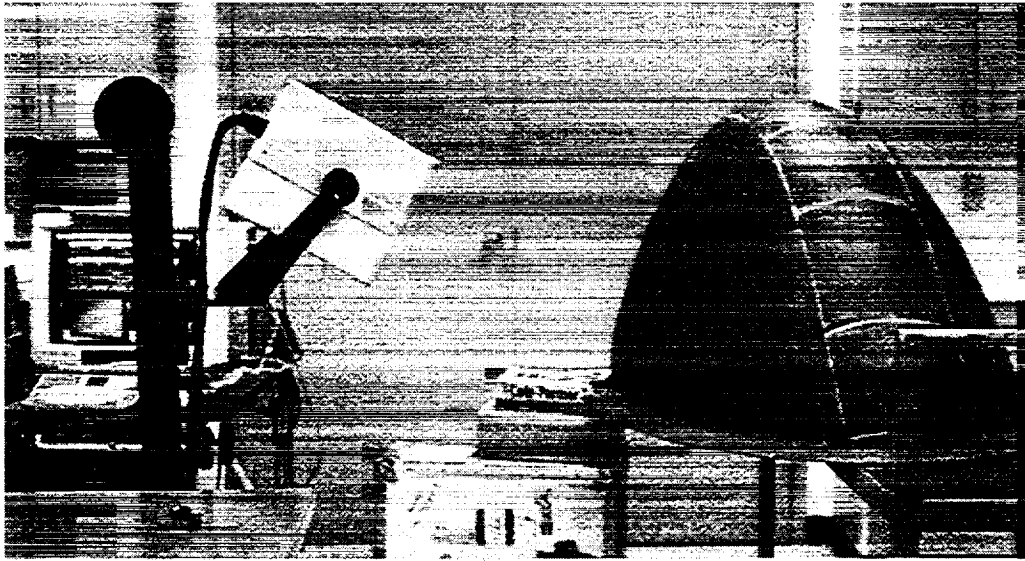


Position 7



Position 8

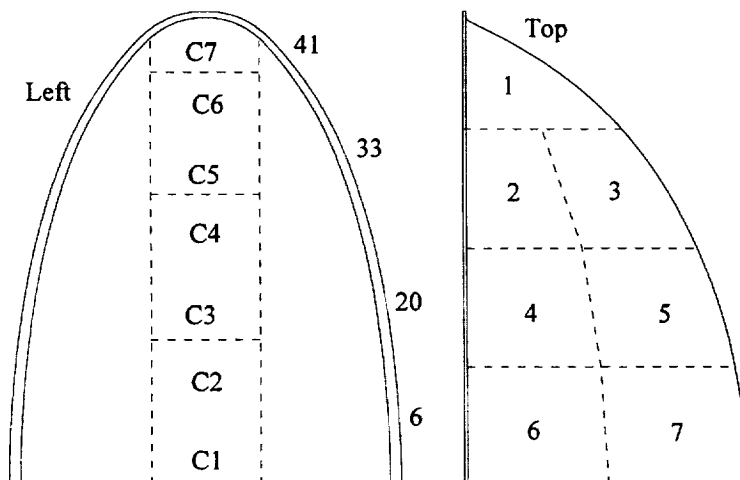
5.7 LO₂ Feedline Fairing For External Tank



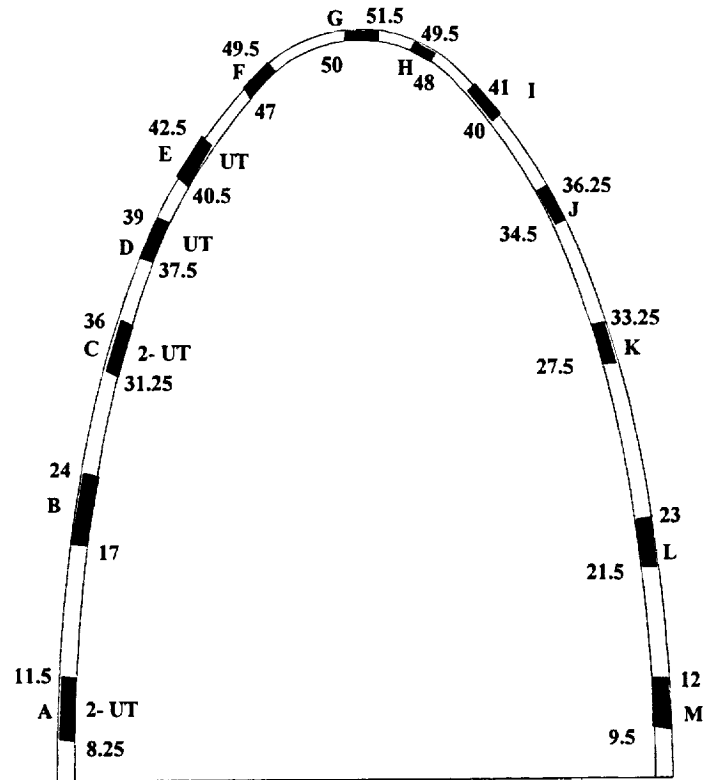
The LO₂ feedline fairing had been inspected with ultrasonics and six regions were found to be defective. The regions were located on the fillet at the base of the fairing and were suspected of containing a large amount of porosity. Otherwise, no defects were intended or suspected.

The structure of the fairing was 18 plies of graphite/polyimide with a built up region 22 ply thick. The fairing was identified with serial number 0008 and part number 80911001355T001.

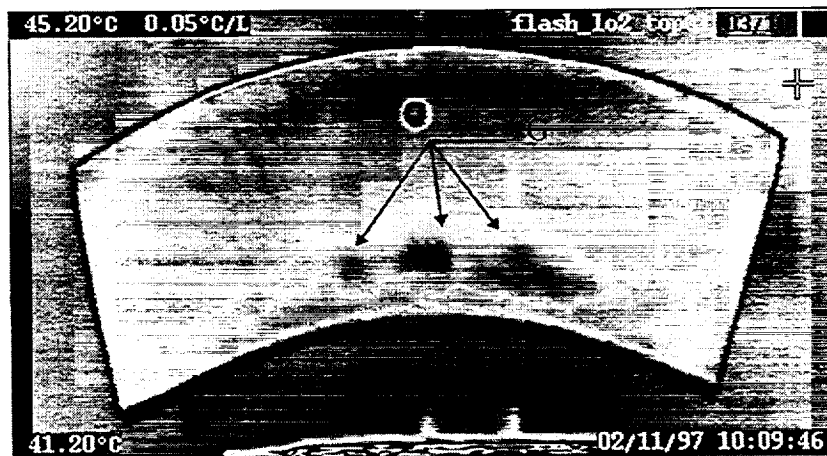
The entire fairing was scanned in 18 inch by 12 inch zones utilizing backside heating with a hand held 1000 W IR lamp. The time delay between frames was set to 1.0 sec.

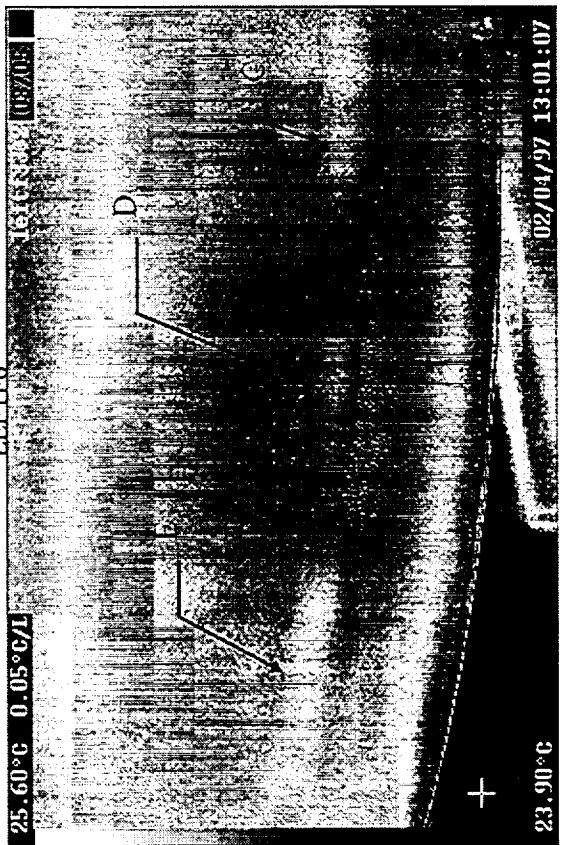
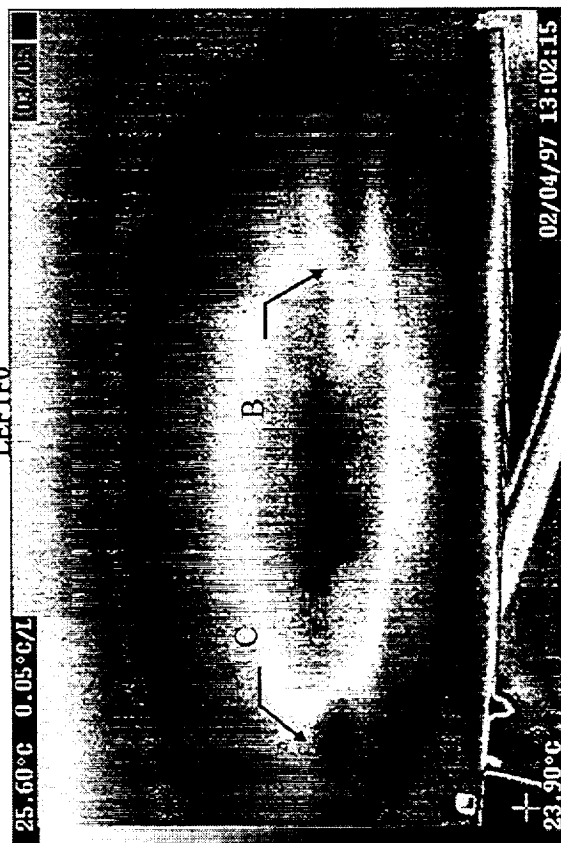
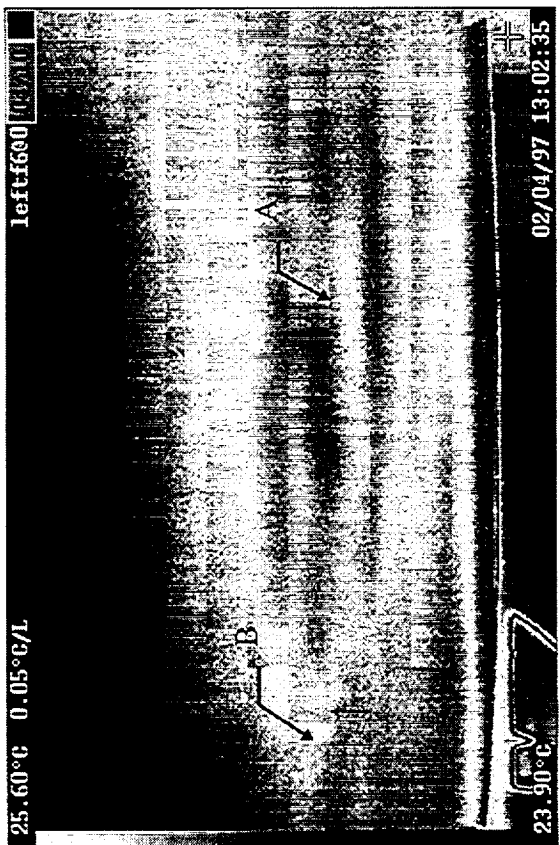
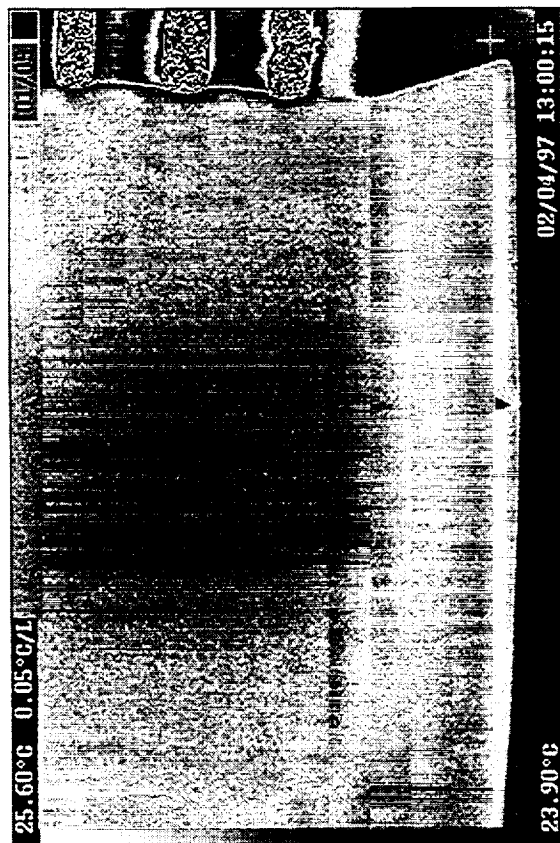


The thermographic inspection yielded 13 potential regions of porosity, including the six previously located by ultrasonics. The following figure outlines the six regions found by UT and the 13 found by thermography. These thirteen regions are also shown on the resulting thermograms.



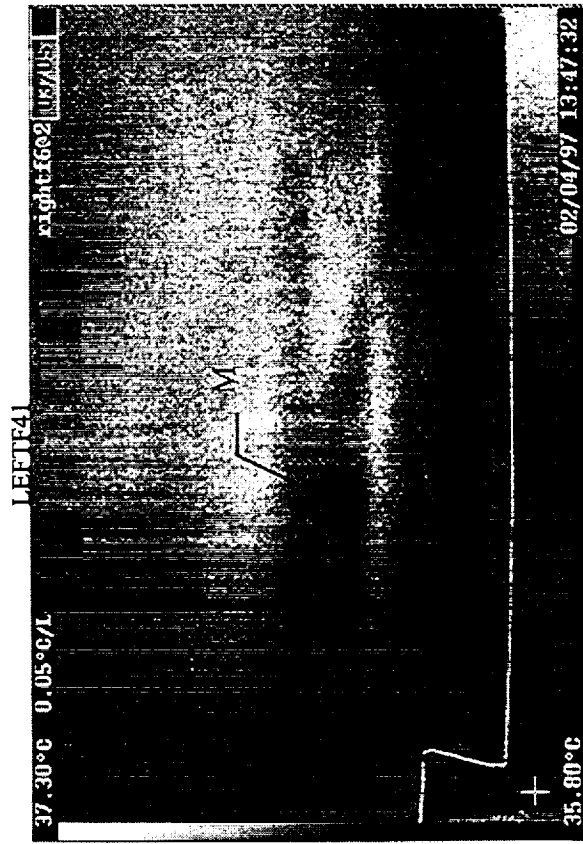
Defect map



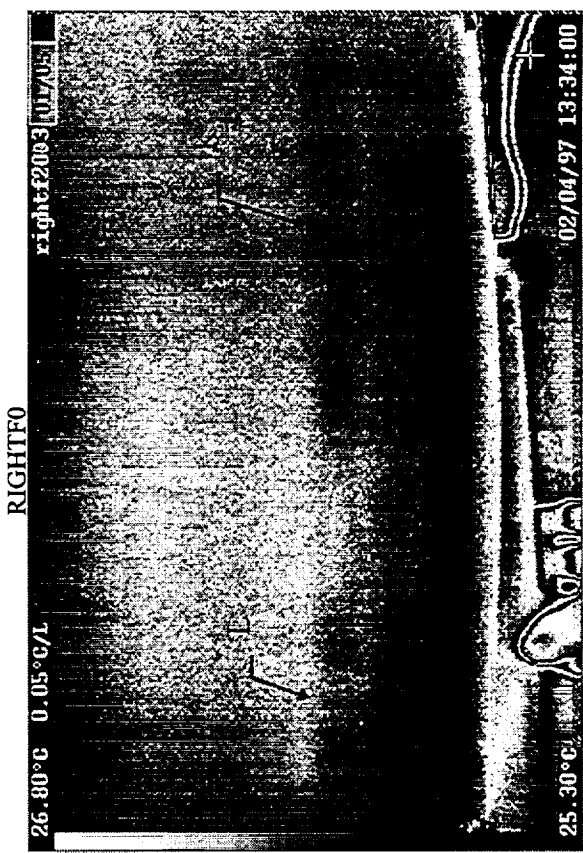
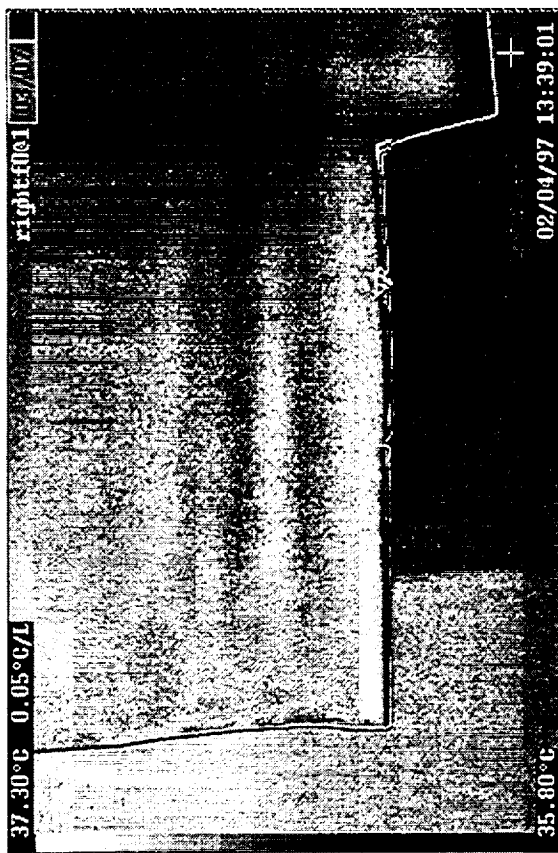


LEFTF20

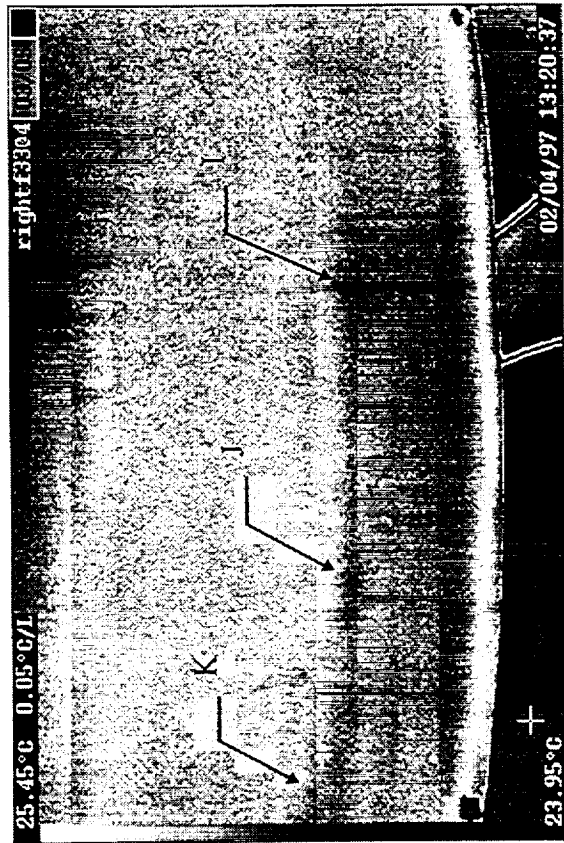
LEFTF33



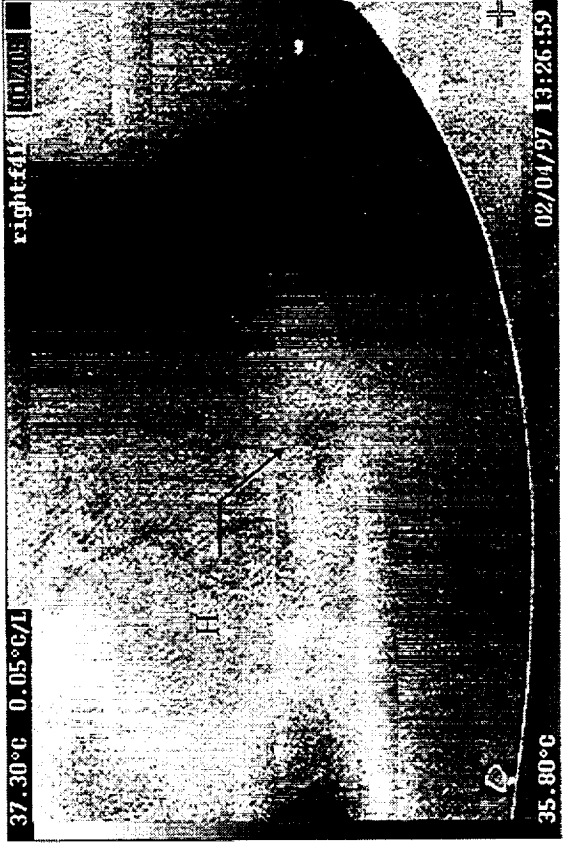
RIGHTF6



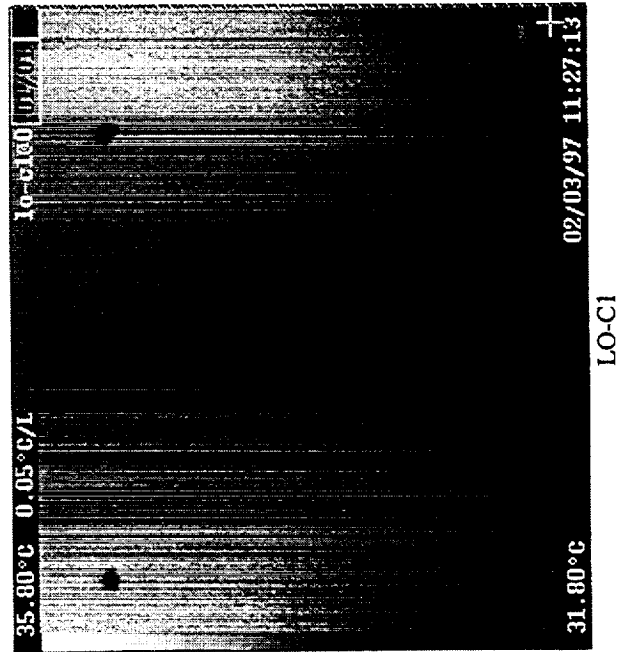
RIGHTF20



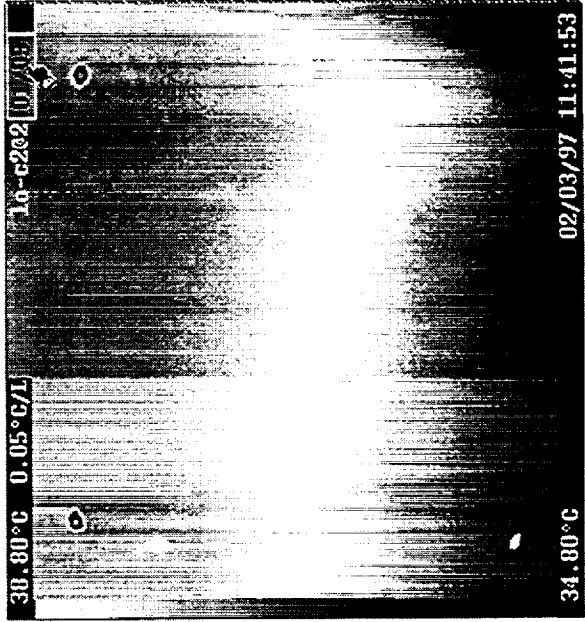
RIGHTF31



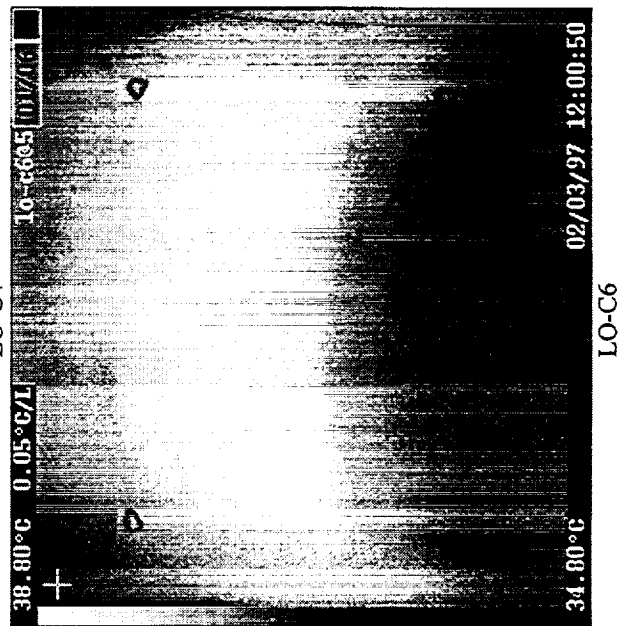
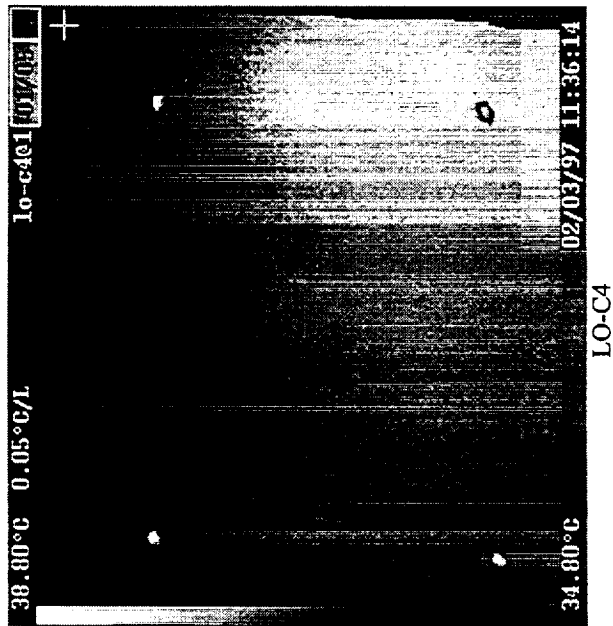
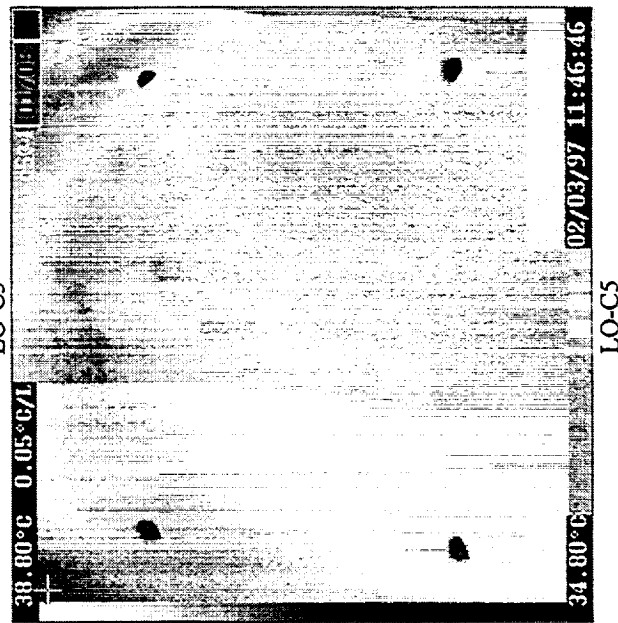
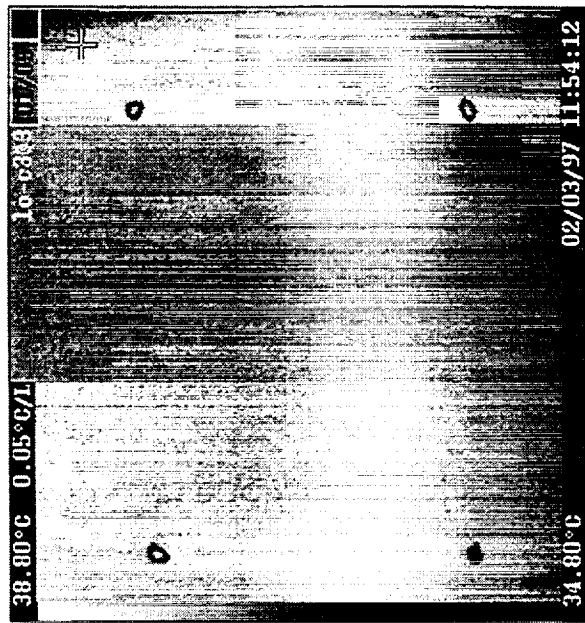
RIGHTF41

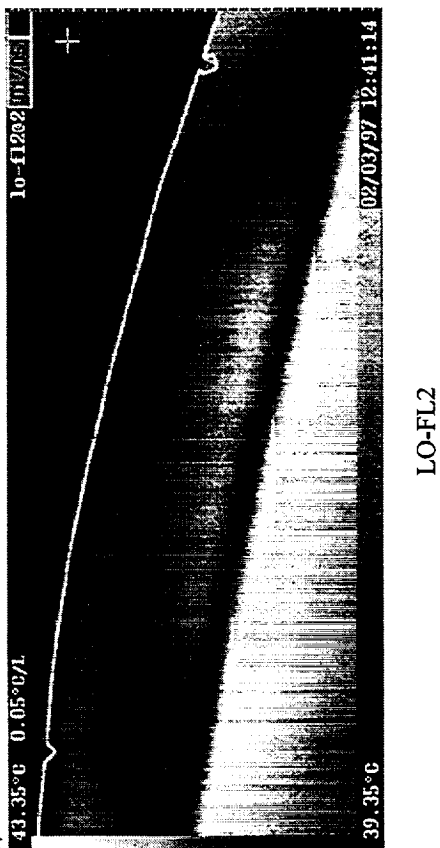
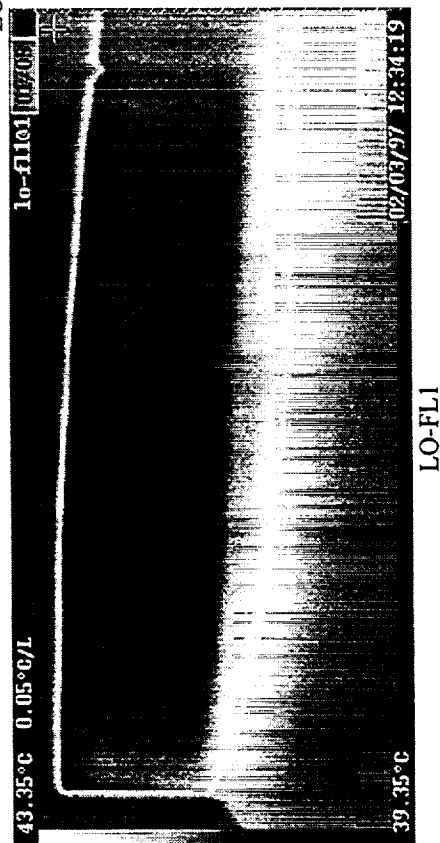
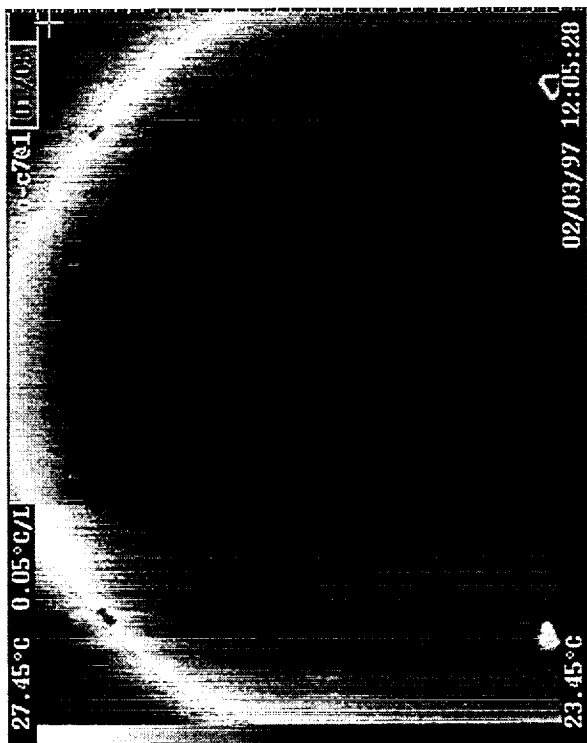


LO-C1



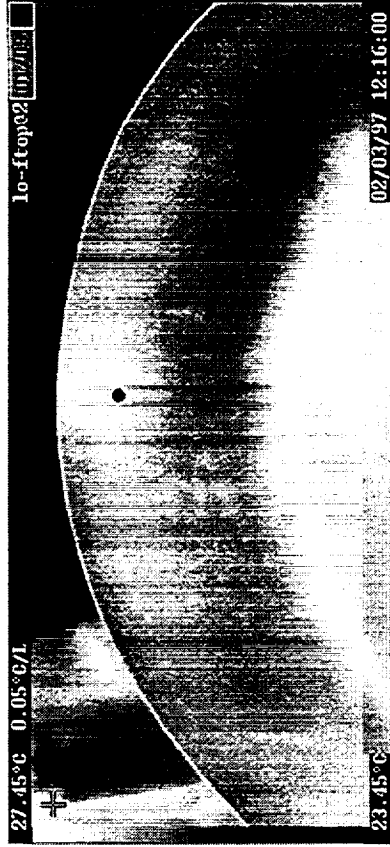
LO-C2



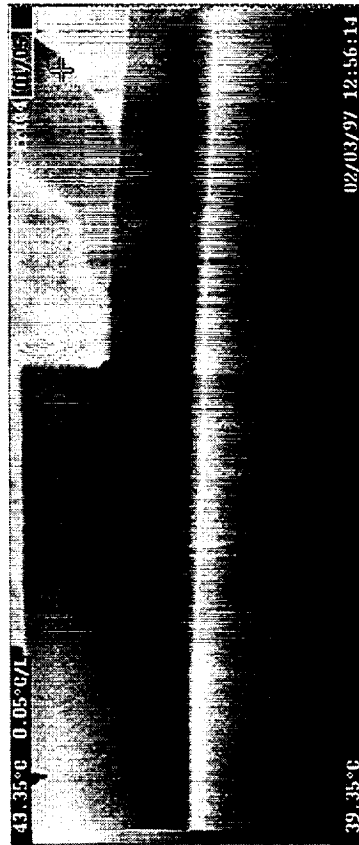




LO-FL3



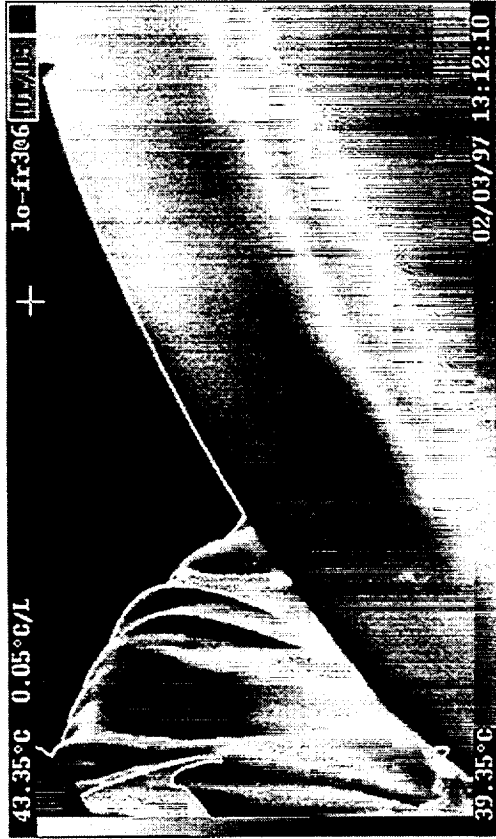
LO-FTOP



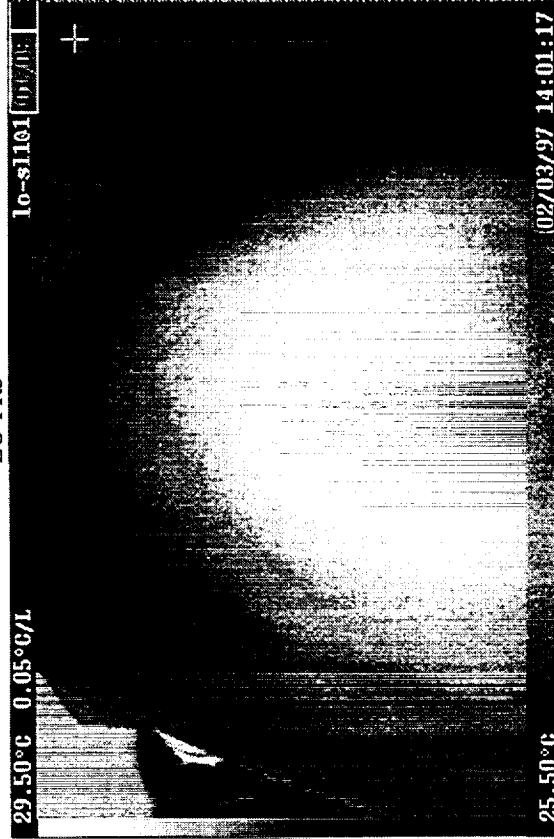
LO-FRI



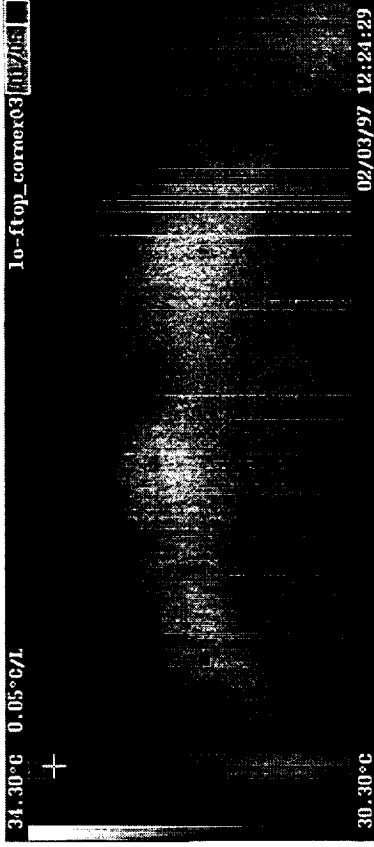
LO-FR2



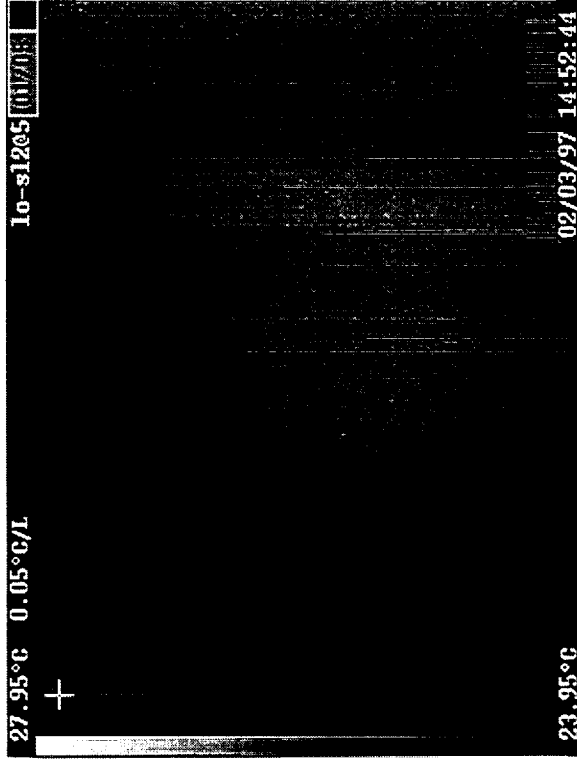
LO-FR3



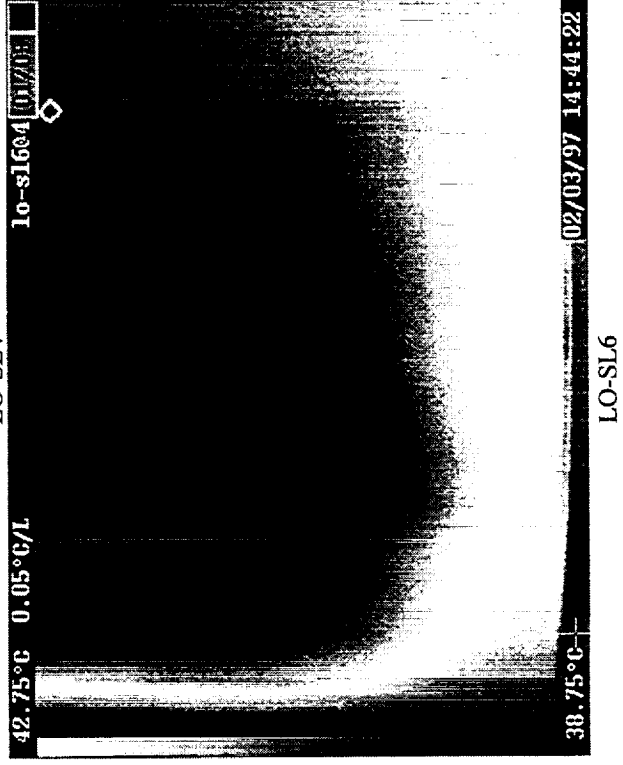
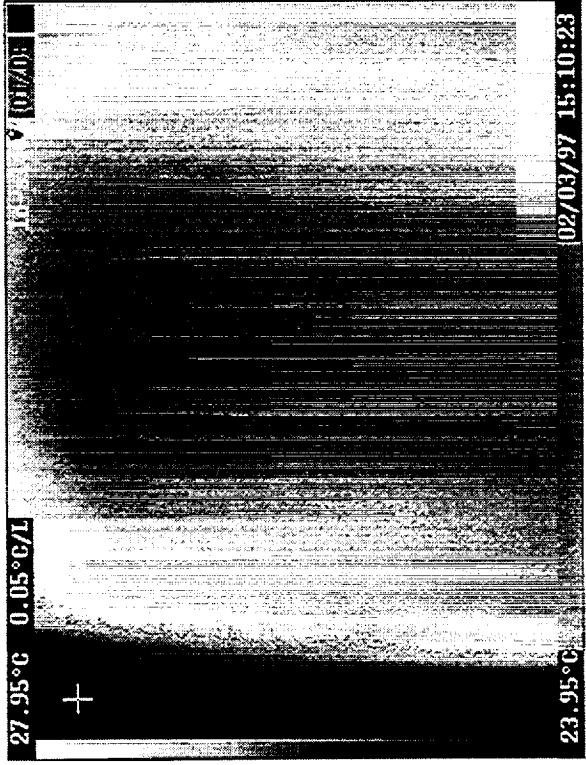
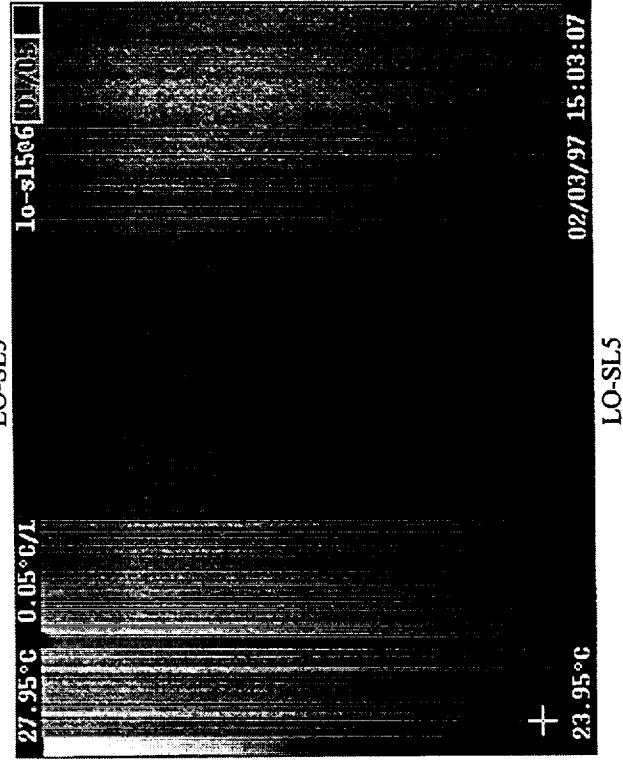
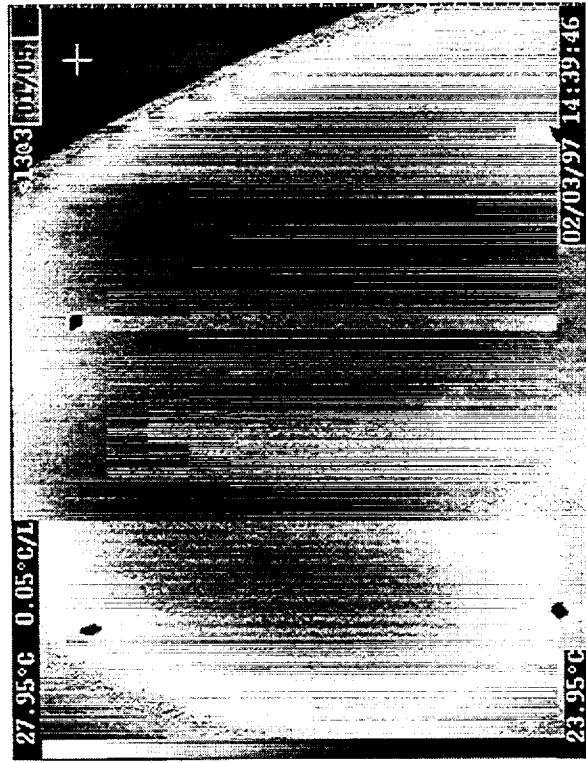
LO-SL1

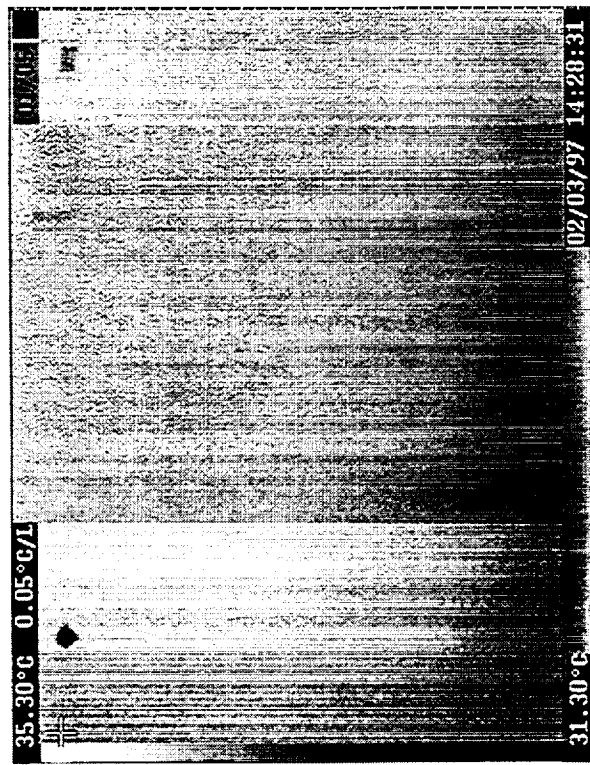


LO-FTOP

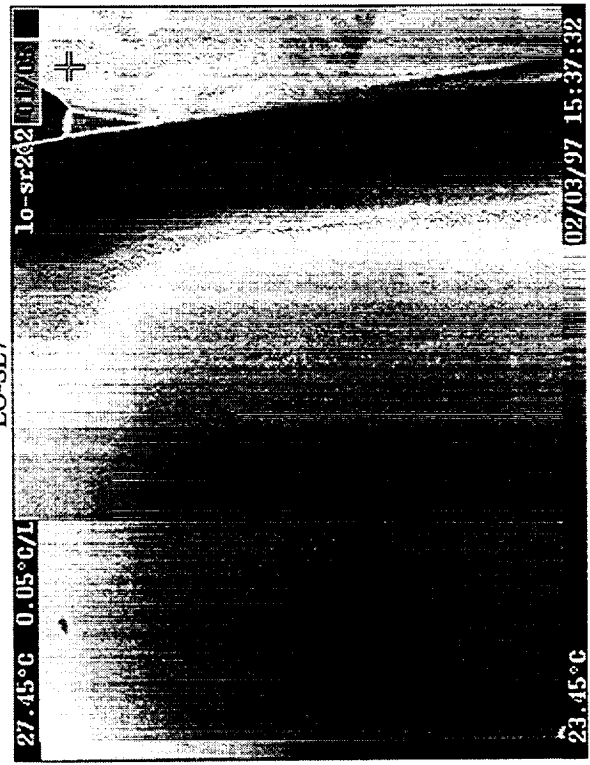


LO-SL2

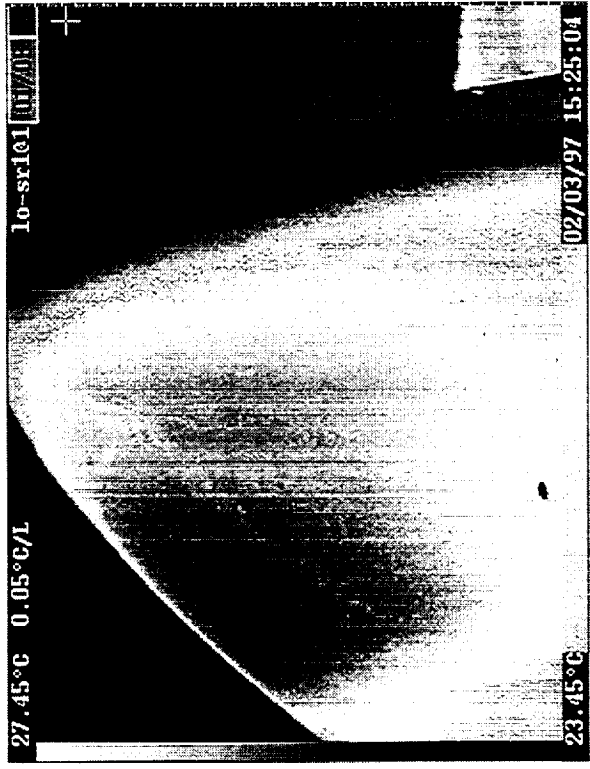




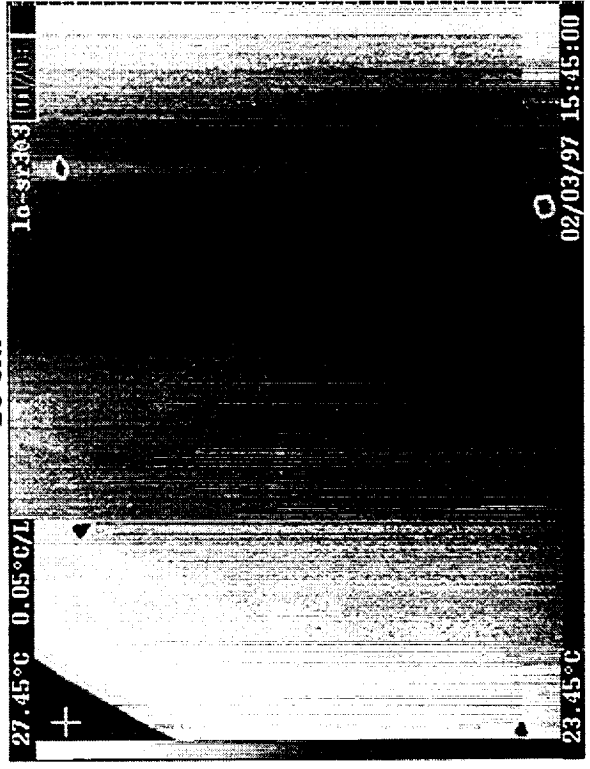
LO-SL7



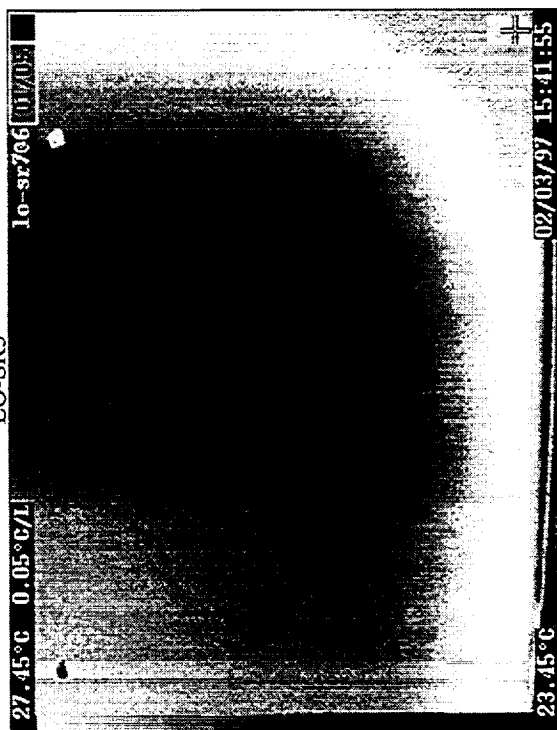
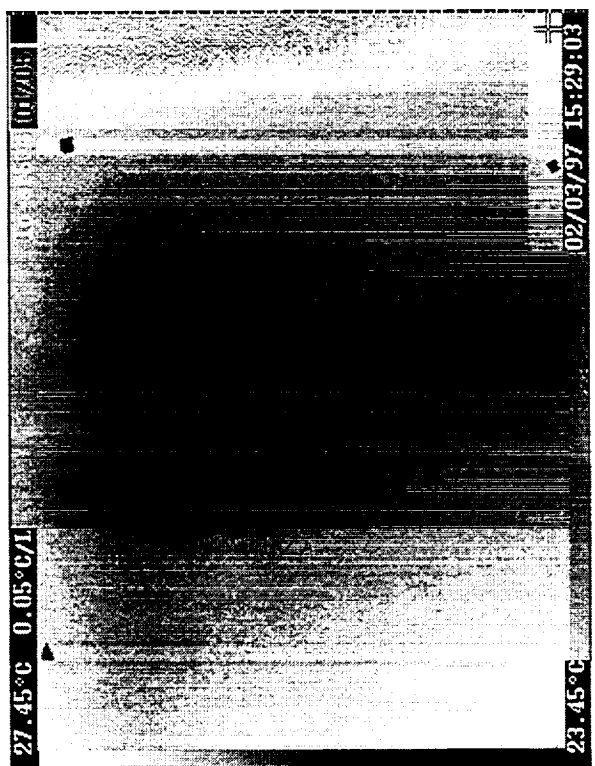
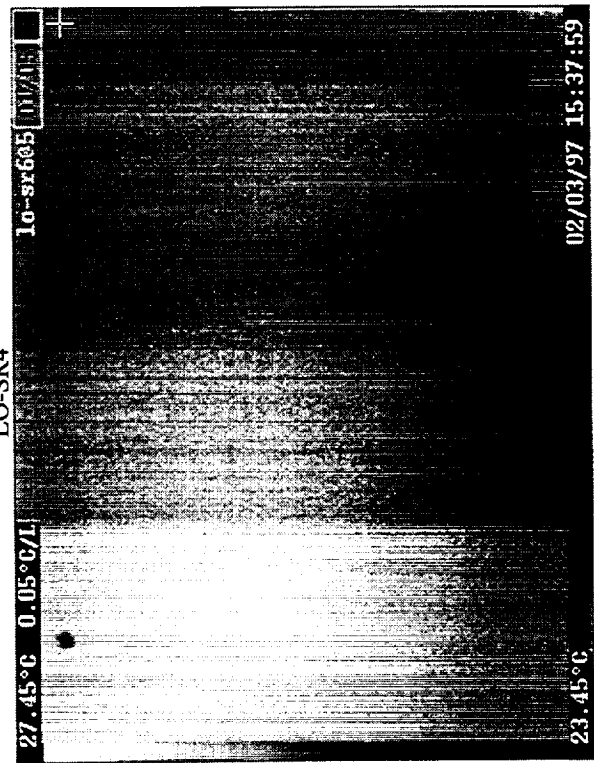
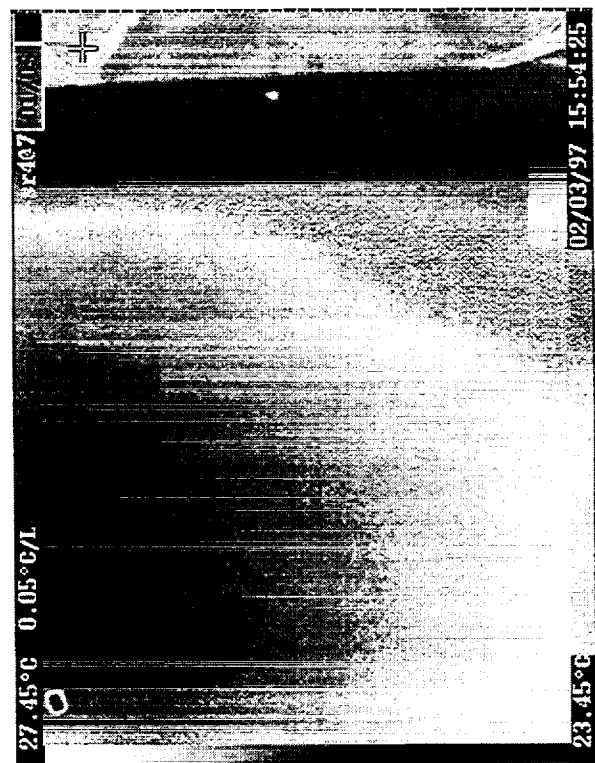
LO-SR2

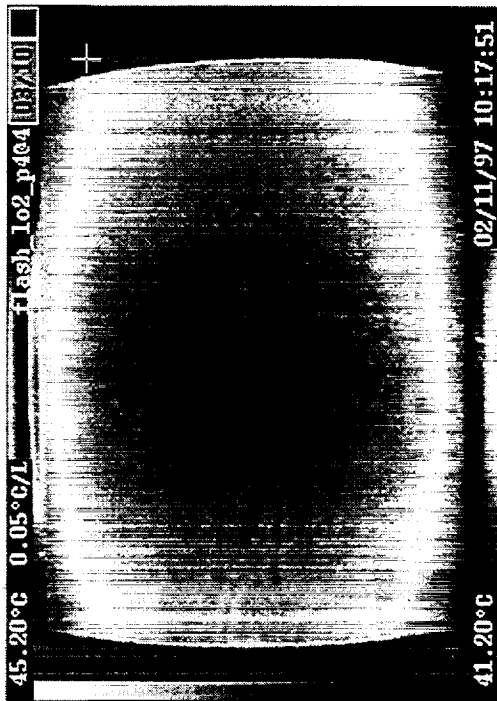
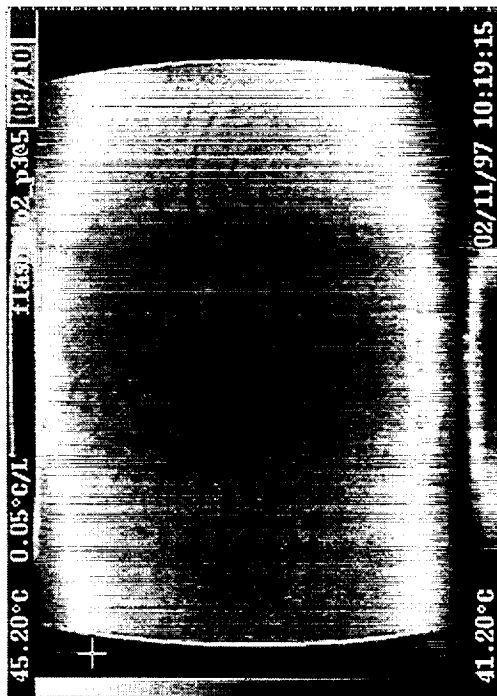
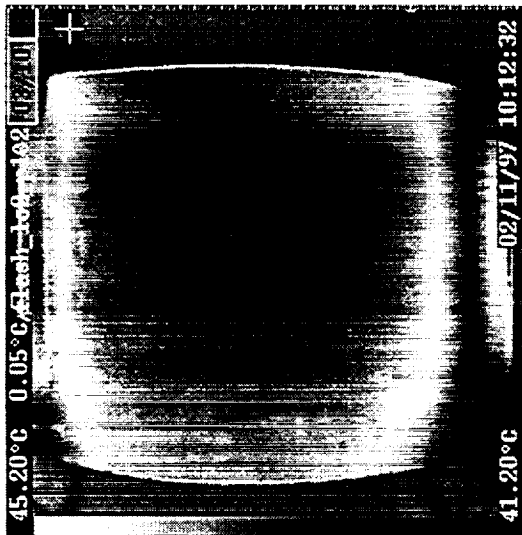


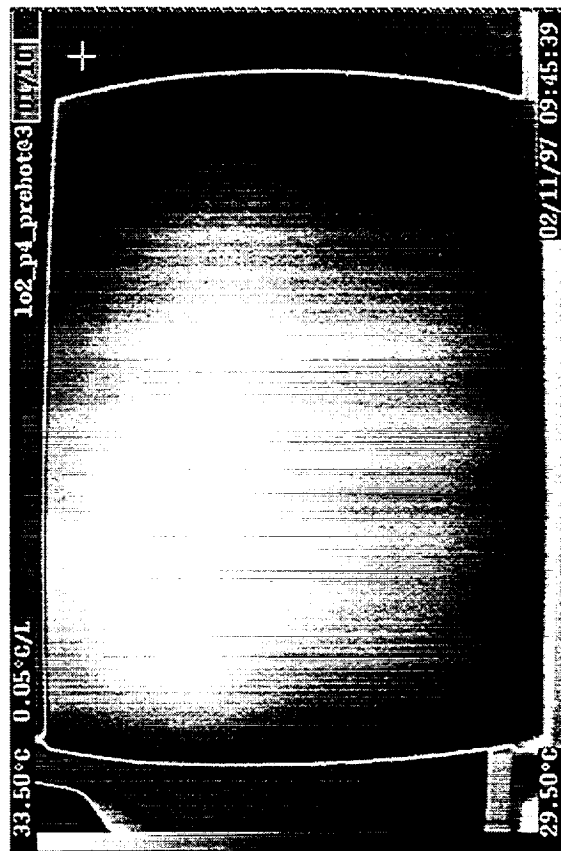
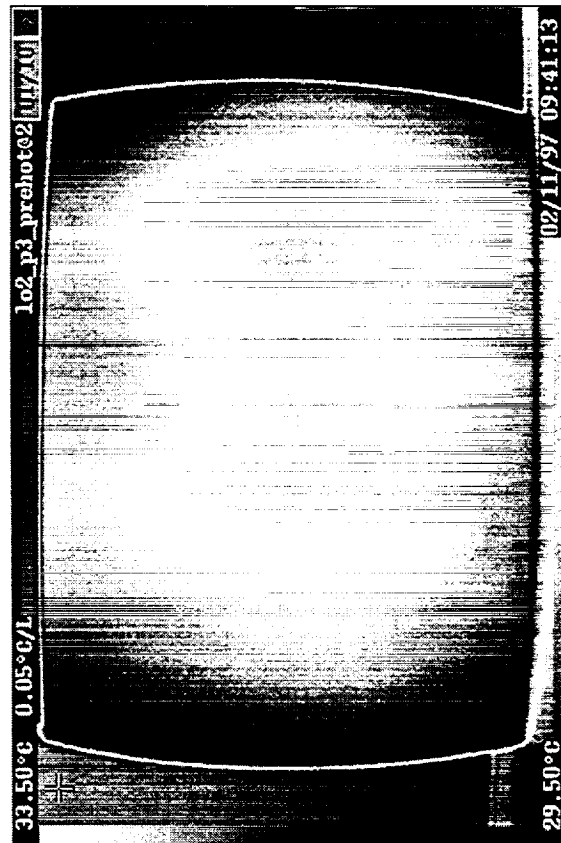
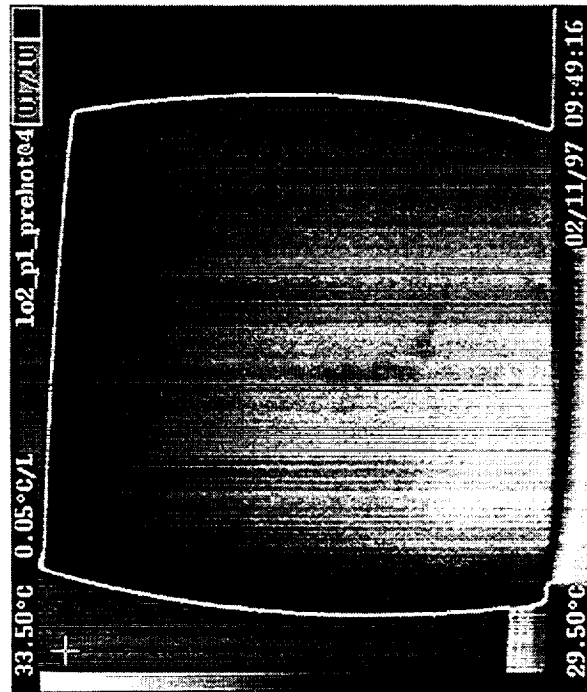
LO-SR1



LO-SR3





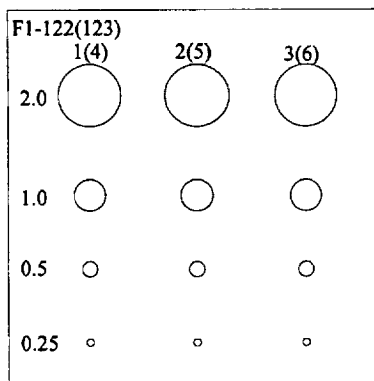


5.8 Thermography of X-38 Panels (Tested at the Johnson Space Center)

A trip to JSC was made to investigate the use of thermography as the primary NDE technique in support of the X-38 Assured Crew Re-entry Vehicle Development Program. Several panels were inspected during the trip including developmental panels of various sizes and a panel with simulated defects.

Panel F122/123 Panel F122/123 was created at JSC to investigate methods to simulate disbonds between the faceplates and core. The panel featured 15 ply, graphite/cyanide-ester faceplates on a nomex honeycomb core. The defects are identified in the following figure.

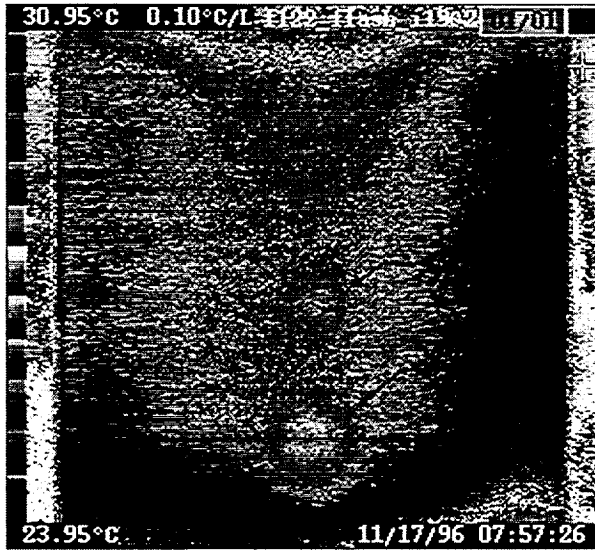
- Defects:
- | | |
|----------------------------|--|
| 1. Teflon inserts | 4. Milled core |
| 2. Missing cobond adhesive | 5. Teflon insert |
| 3. Release agent | 6. Missing adhesive filled with cured adhesive |



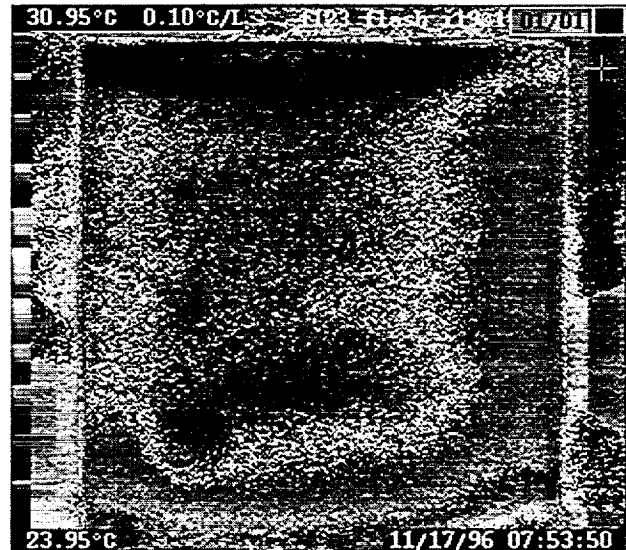
The panel was inspected with the Bales TIP utilizing both flash and manual heating. During flash heating a 1500v power setting was used and the panel imaged a distance of 32 inches. The images were taken with a 20 msec per frame delay. Manual heating was conducted using the 1000 W infrared heat lamp and the images taken with a 0.5 sec delay between frames.

The results of these tests revealed that only the 2.0, 1.0 and 0.5 inch diameter “missing cobond adhesive” defects were identifiable during flash heating. No thermal indications were found using either front or back side manual heating. In fact it was noticed that it was very difficult to get heat through the panel during manual back side heating. Image filtering through convolution with a simple edge enhancement filter helped to identify the defects

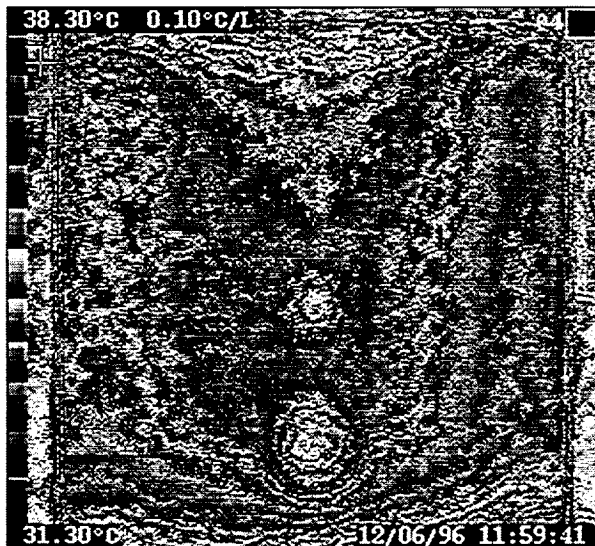
0	0	0	0	0	0	0
0	2	2	2	2	2	0
0	2	0	0	0	2	0
0	2	0	10	0	2	0
0	2	0	0	0	2	0
0	2	2	2	2	2	0
0	0	0	0	0	0	0



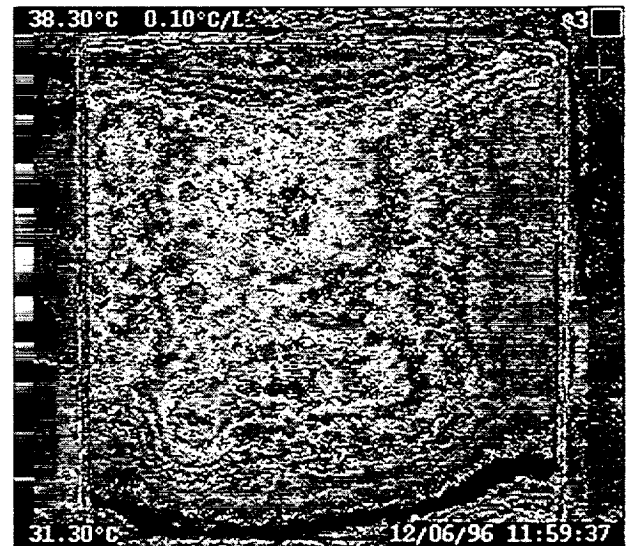
F122 (Missing cobond adhesive defects)



F123 (Cured adhesive inserts)



F122 Filtered



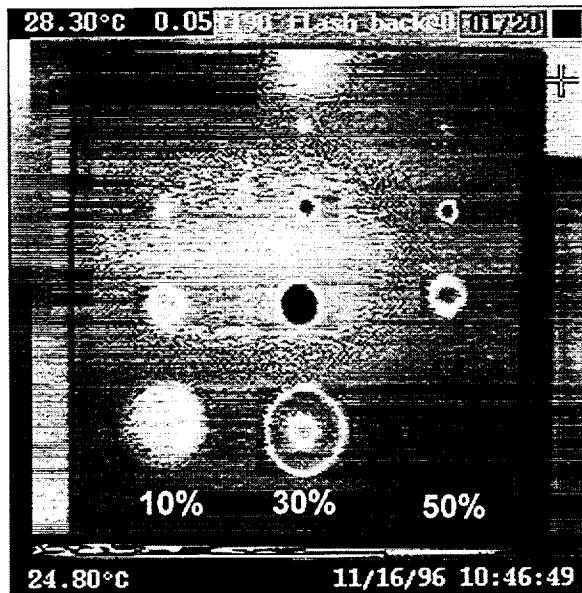
F123 Filtered

Panel F190 Panel F190 was constructed to simulate defects within the faceplates themselves. Here, Teflon inserts at 50%, 70% and 90% depth when viewed from “label” side were built into the panel. As with the honeycomb panel the faceplate was constructed from 15 plies of gr/cf.

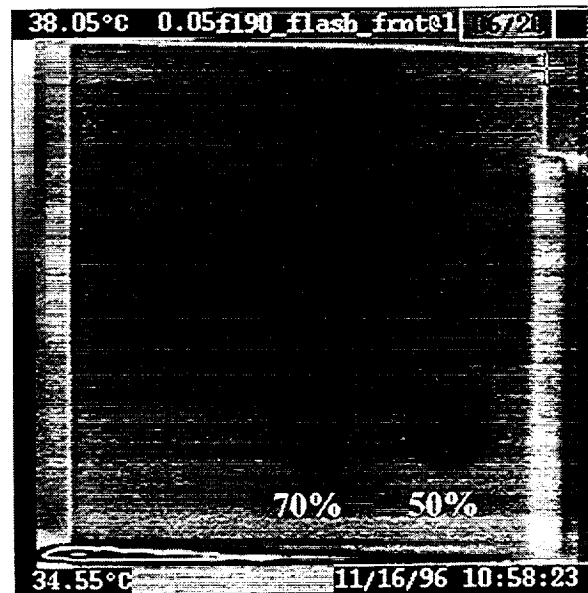
The panel was inspected with the Bales TIP system utilizing front side flash heating (1500v) power setting from a viewing distance of 32 inches. The delay between frames was set to 20 msec.

All scheduled defects were found when the back side of the panel “the opposite side from the label” was imaged. These defects are at a depth of 10%, 30% and 50% into the panel.

When the panel was imaged from the label side so that the defects were at 50%, 70% and 90%, all but the deepest flaws were found. Flash thermography appears to be penetrating approximately 11 to 12 plies into the laminate.



F190 (Back side)

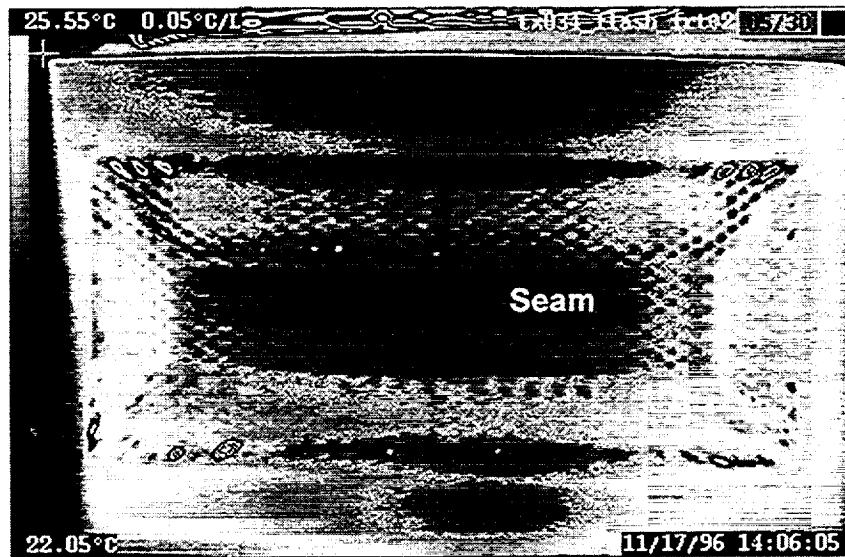


F190 (Front side)

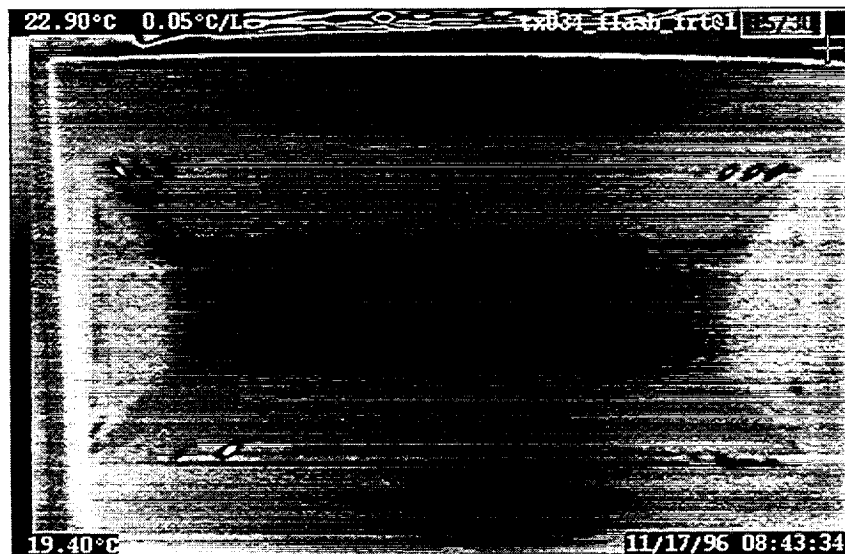
Panel TX034 Panel TX034 was built to test the ability of the workers at JSC to construct a honeycomb panel of similar thickness to that of the X-38. The only known defects in the panel was a seam in the core which was known to bisect the panel.

The panel features 15 ply gr/ep faceplates over a honeycomb panel sealed at the edge to form a 30 ply joint. As before, the Bales TIP system was configured for front side flash heating with a viewing distance of 32 inches and a power setting of 1500v. And as typical with flash heating the time delay between frames was set to 20 msec.

The seam is apparent in the thermogram. Also, several hot regions were detected at the fillet between the honeycomb and the edge of the panel indicating possible voids. No thermal abnormalities were apparent during the inspection of the back side of the panel.



TX034 (120 msec)



TX034 (320 msec)

Panel PF2 As with the TX panel, panel PF2 was constructed to test manufacturing practices, and as such had no known or preplanned in defects. The panel featured a nomex honeycomb core covered with 15 ply gr/cf face plates. At the edge of the honeycomb core the faceplates stepped up to 24 plies then merged (top and bottom) at the edge to yield 48 ply seam.

The PF2 structure was scanned in 12 segments per side using front side flash heating (1500v) and a 20 msec frame delay.

S10	S11	S12
S9	S8	S7
S4	S5	S6
S3	S2	S1

FRONT

S3	S2	S1
S4	S5	S6
S9	S8	S7
S10	S11	S12

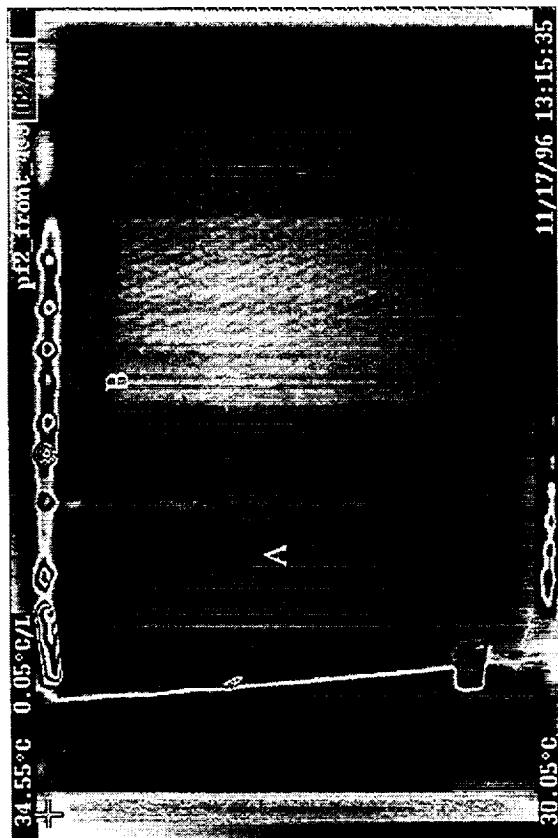
BACK

The thirteen regions shown in images Front 4, 6 and 9 along with images Back 2, 7, 9 and 10 represent the worst of the thermal abnormalities found. These thermal indications had little or no surface features.

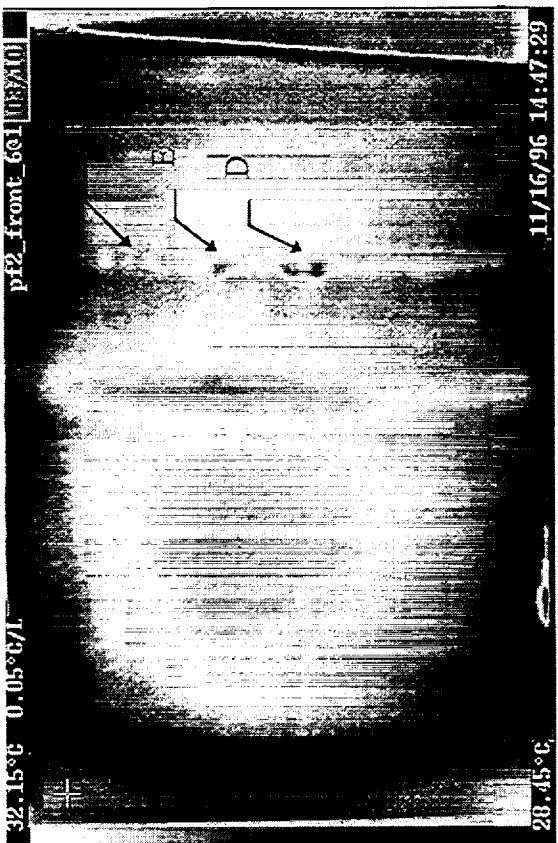
The complete thermogram of the panel is also given for reference.

Panel EX037 Panel EX037 was constructed from 16 plies of gr/ep and measured 24"x 49". No scheduled defects were built into the panel. The panel was scanned in 6 segments per side using front side flash heating (1500v) and the Bales TIP. The frame delay was set to 20 msec.

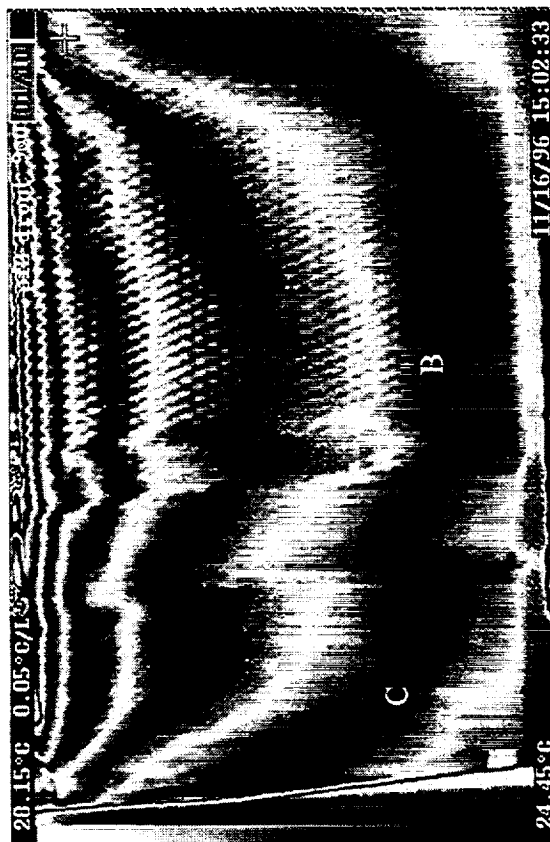
The only defects found were a small abnormality located on the front side in quadrant 2 and 3.



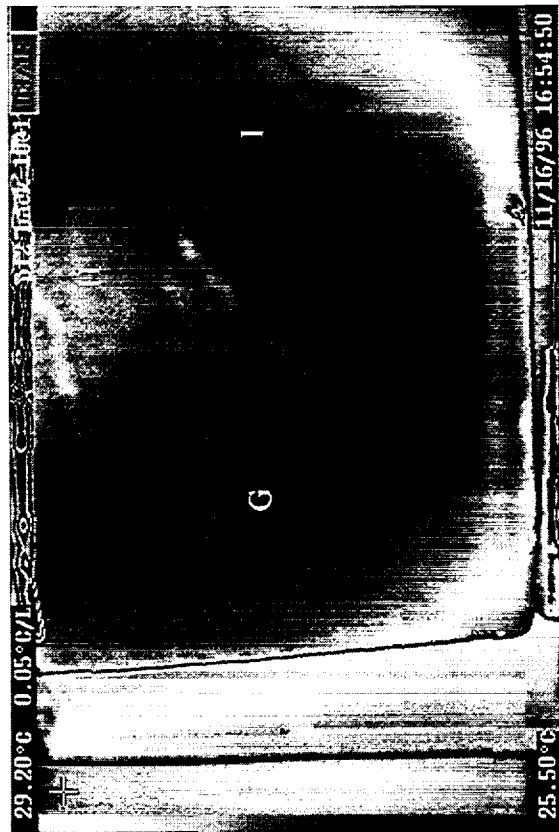
Front 4



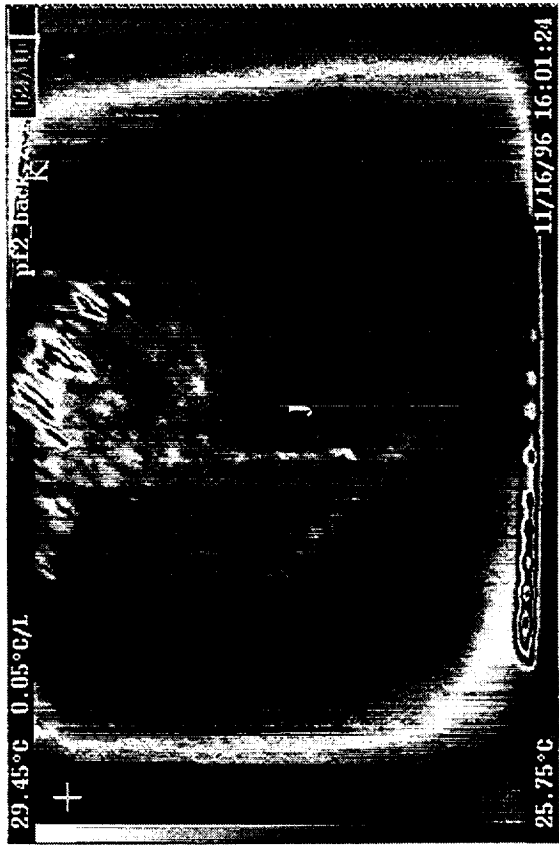
Front 6



Front 9



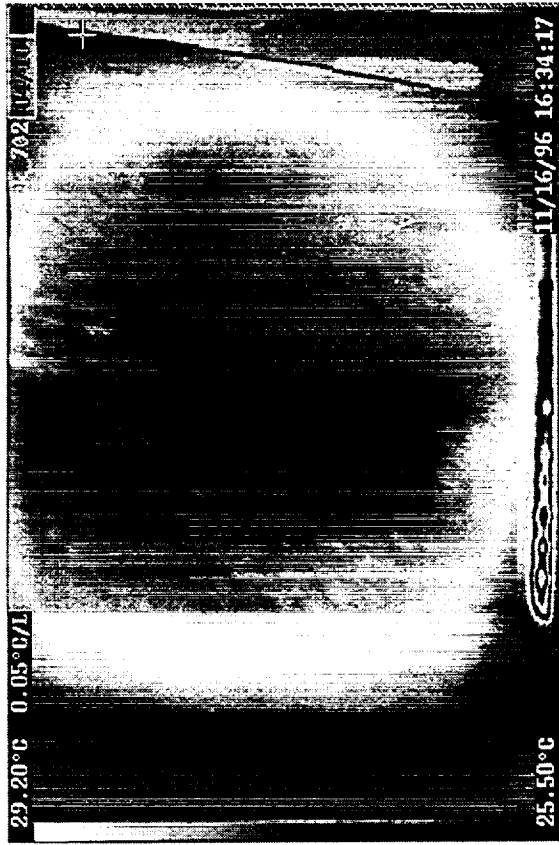
Back 10



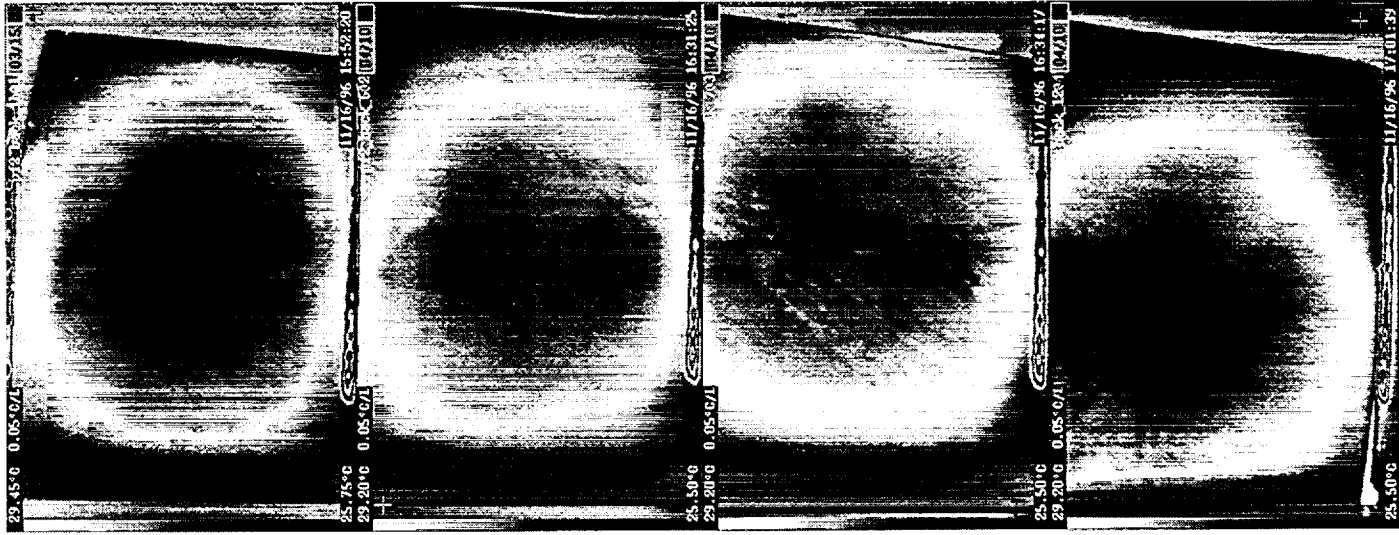
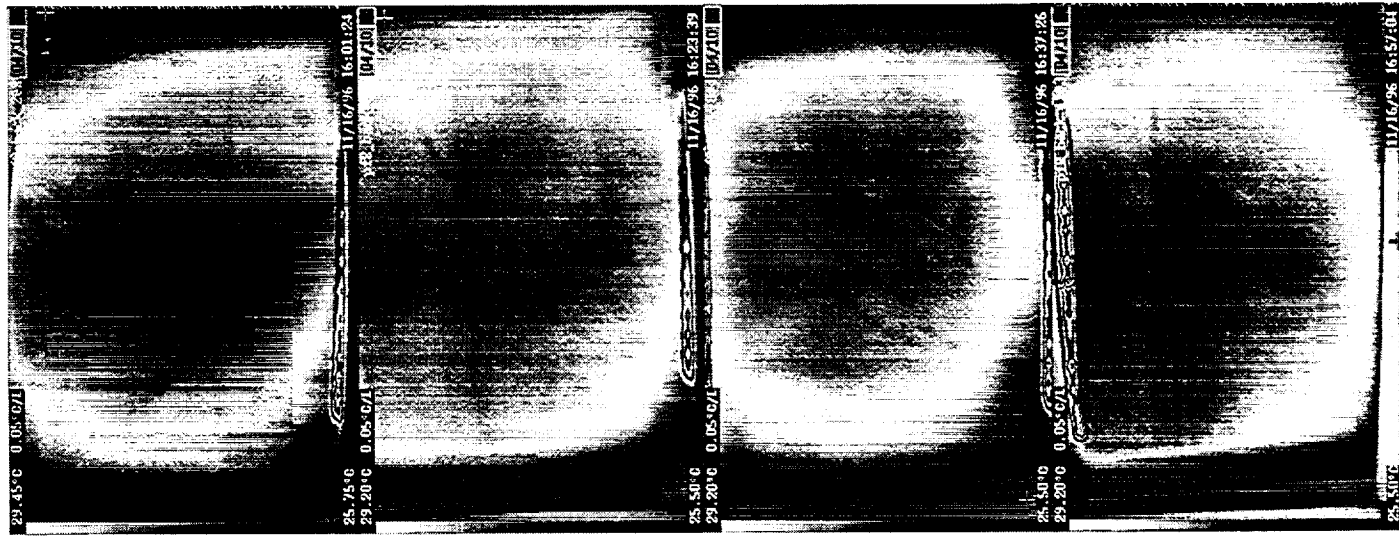
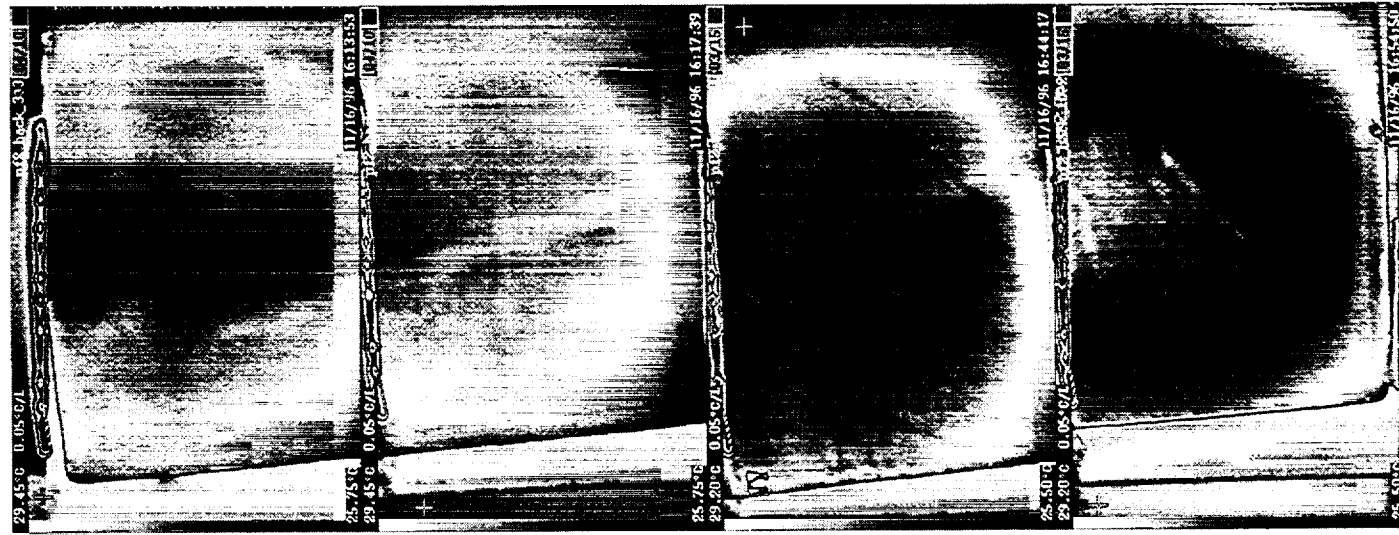
Back 2

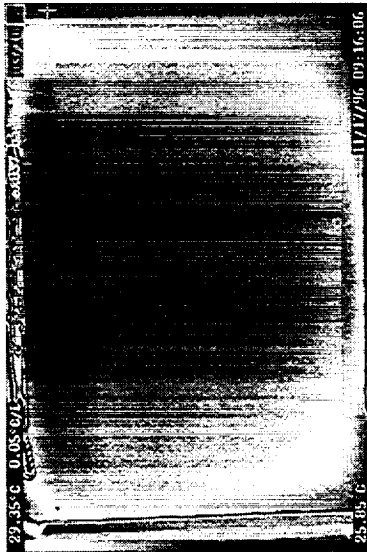


Back 9

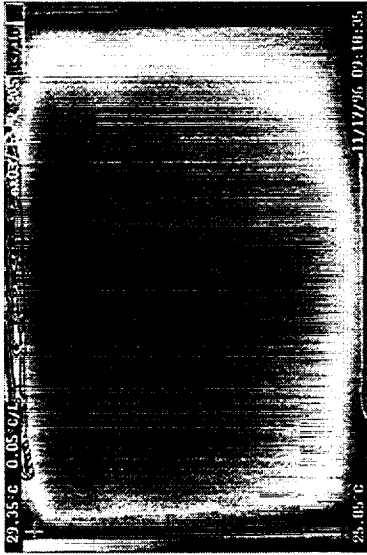


Back 7

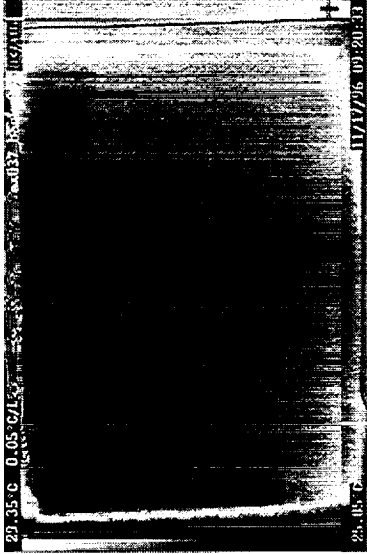




Quadrant 6 (Back)

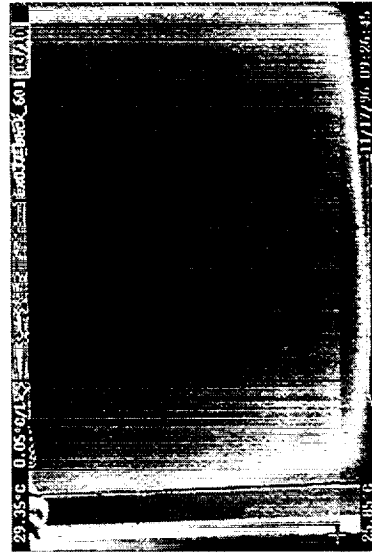


Quadrant 5 (Back)

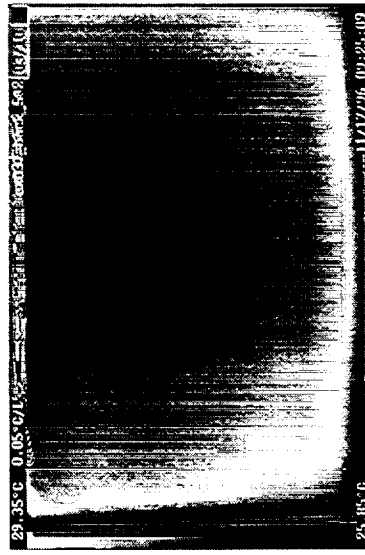


Quadrant 4 (Back)

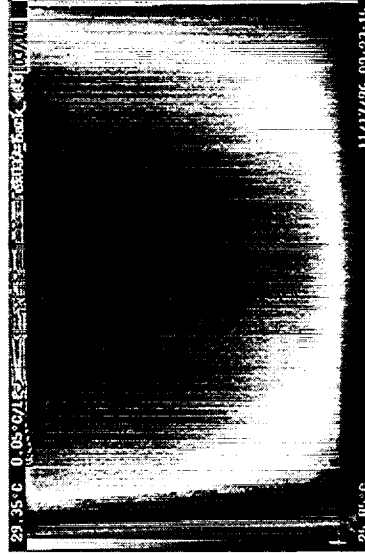
EX037



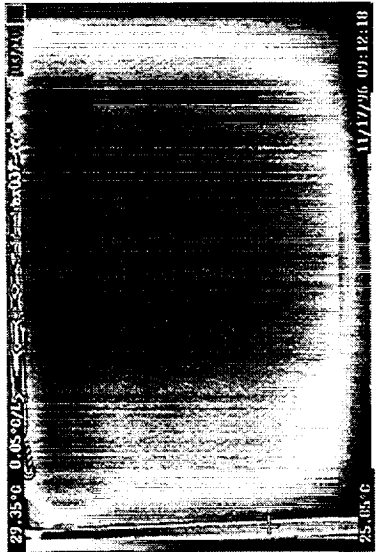
Quadrant 1 (Back)



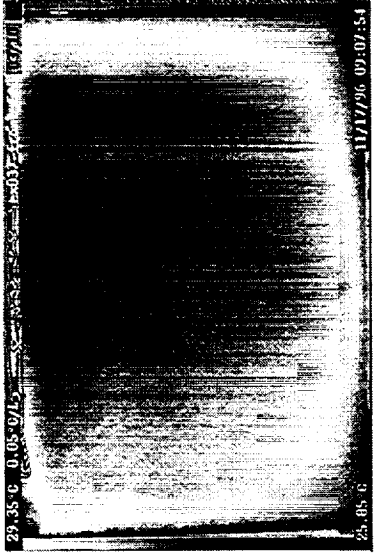
Quadrant 2 (Back)



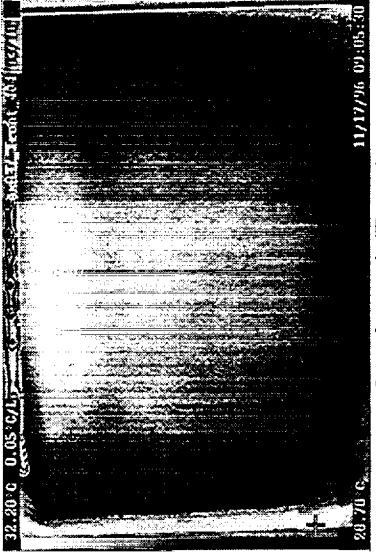
Quadrant 3 (Back)



Quadrant 6 (Front)

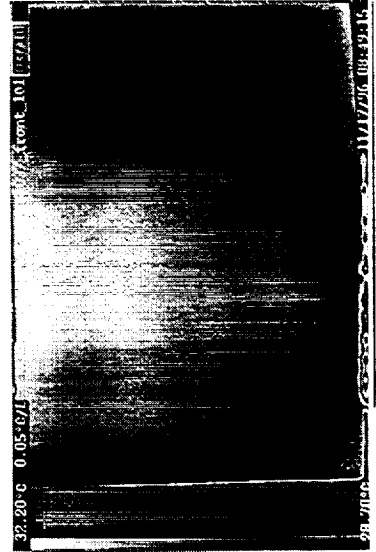


Quadrant 5 (Front)



Quadrant 4 (Front)

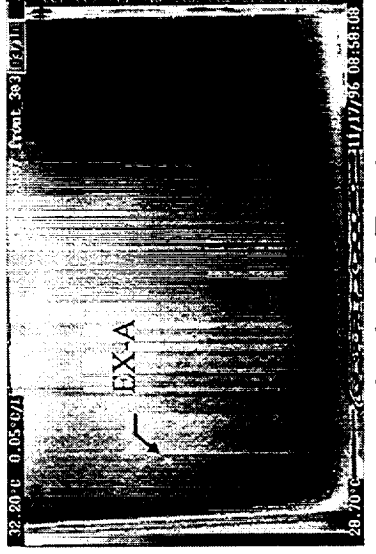
EX037



Quadrant 1 (Front)



Quadrant 2 (Front)



Quadrant 3 (Front)

5.9 Kevlar Filled Urethane Insulation (KFUI) Test Panels for the Advanced SSME Turbopump

In response to the need to develop inspection methods for the insulation jacket around the SSME turbopump housing a series of inspections were conducted on specially designed test panels. The panels were supplied by DuPont and featured simulated defects "inserts" beneath the top layer for each specimen. Four specimens were supplied as indicated in the following table.

Specimen	Construction
A	Metal-Kevlar Roving
B	Metal-Kevlar Roving-KFUI foam
C	Metal-Kevlar Roving-KFUI foam-Kevlar roving
D	Metal-Kevlar Roving-KFUI foam-Kevlar roving (No inserts)

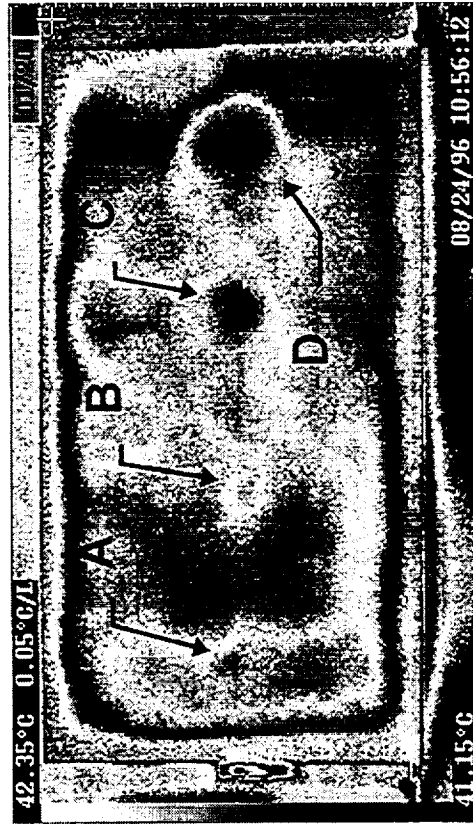
The panel was inspected with the Bales TIP utilizing both flash and manual heating.

Image 1 was acquired with front side heating by a hand held heat gun. The time delay between images was set to 100 msec and images 2 through 21 were archived. In this image all four scheduled defects can be seen. When specimen A was excited with flash heating only the largest three defects could be found.

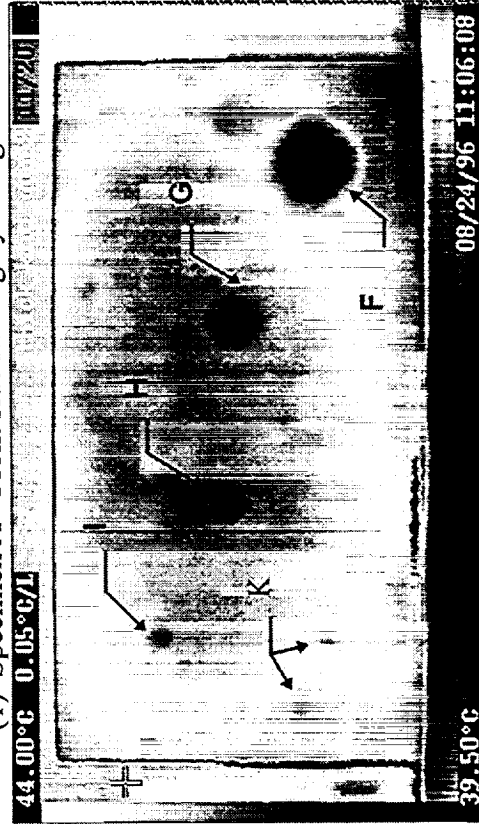
Specimen B had inserts in the same position as specimen A. Image 2, produced by back side long duration heating by 2 - 500W heat lamps only showed the largest of these two defects, as one defect. No other heating method produced as good a results as the back side heating used for this image.

Specimen C is seen in images 3, 4 and 6. In images 3 and 4 a heat gun was used for the thermal excitation and the time delay set to 1 sec/frame. Image 6 was acquired with flash heating and time delay of 0.5 sec/frame. It is interesting to see that the flash imaged flaws are better defined than those obtained with manual heating, but not all flaws are found with flash heating.

From these results, thermography was found only to be useful for inspecting beneath the kevlar roving. It would not be possible to detect flaws beneath the KFUI with any degree of confidence. This intern implies that inspection of the fully assembled insulation blanket would only be capable of finding defects below the first layer of Kevlar.



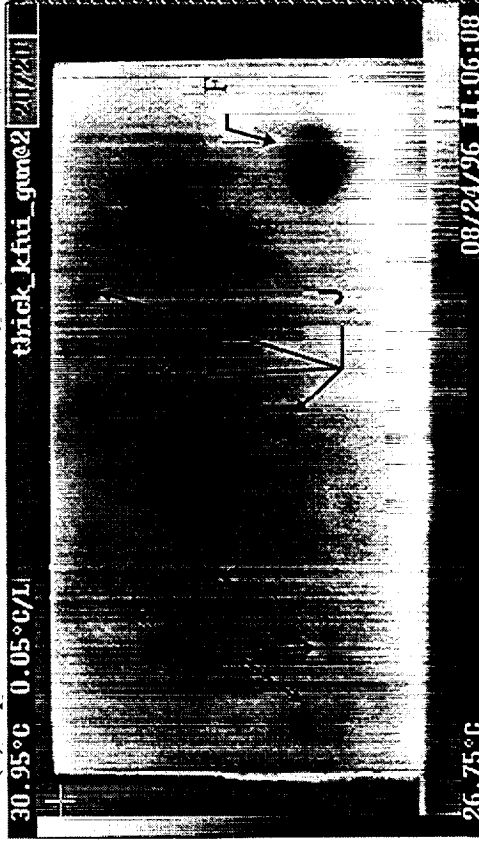
(1) Specimen A - Front side heating by heat gun



(3) Specimen C - Front side heating by heat gun



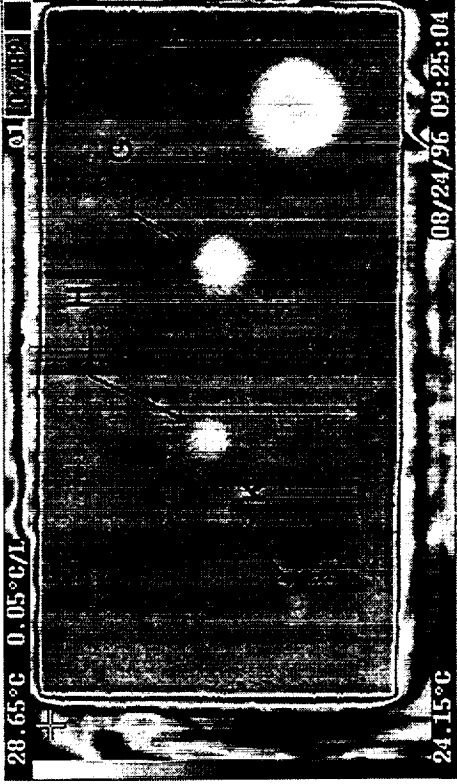
(2) Specimen B - Back side heating by 2-500 W lamps



(4) Specimen C - Front side heating by heat gun



(5) Specimen A - Flash lamp heating



(6) Specimen C - Flash lamp Heating

5.10 Thermography of SXI

A graphite/epoxy tube for SXI was inspected utilizing front "viewing" side flash and manual heating from the Bales TIP. The power setting of the flash lamps was set to 1400v and the tube was imaged at a distance of 16 inches. During manual heating a hot air blower was utilized and the tube imaged at 10 inches. The delay between frame acquisition was set to 20 msec for flash heating and 0.5 seconds for manual heating. Frames 2 through 11 have been saved for archival purposes on laser disk.

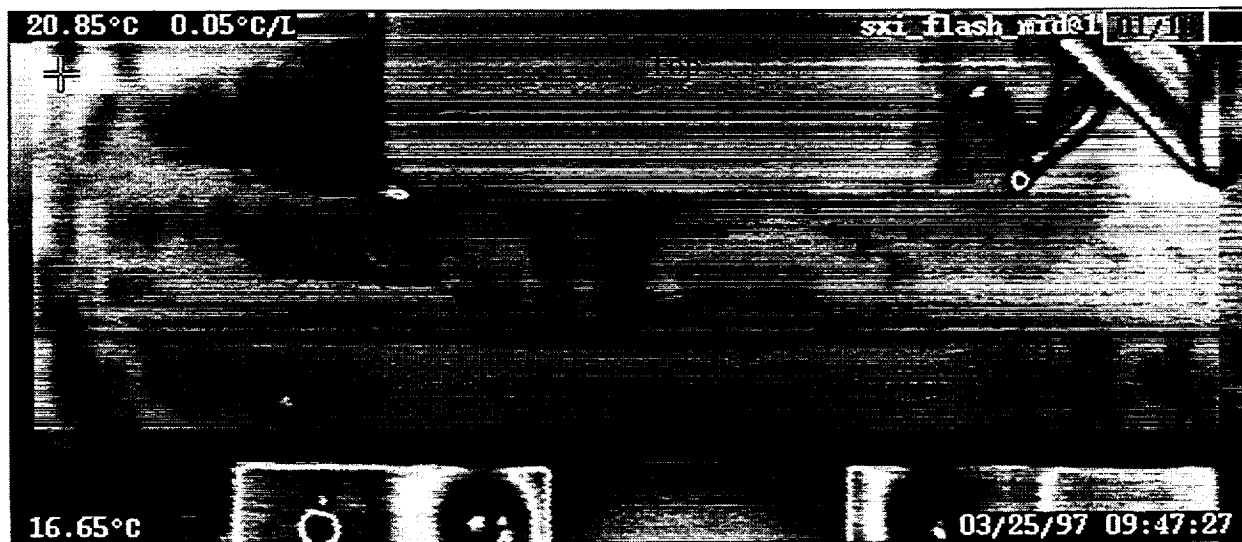
The tube was inspected after failing a structural load test. In that test, the top attachment points tore loose. Of primary interest was the inspection of the mid-attach points where the mount had pivoted when the upper mount failed.

The images (both flash and manual heating) of where attachment pad 1 and 2 tore loose clearly show the regions where the tube delaminated upon failure. It was difficult to view the bondline during flash heating. During manual heating though, several discontinuities can clearly be seen. These discontinuities may be cracks "delaminations" formed due to the bending moment applied to the joint when the upper pads failed. The joint would need to be inspected with other NDE techniques such as ultrasonics or x-ray to verify these conclusions.

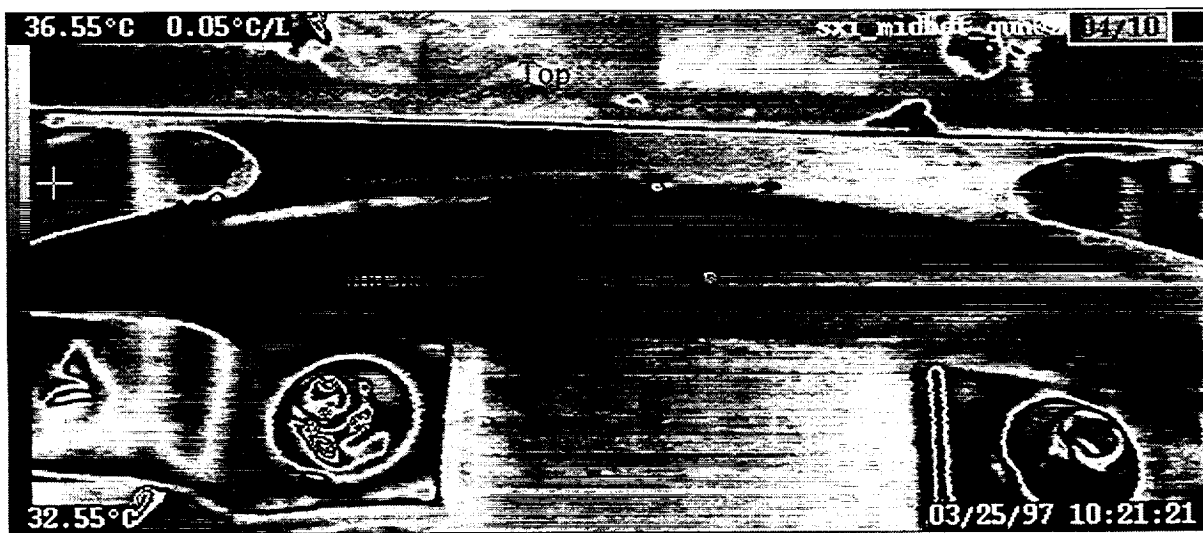
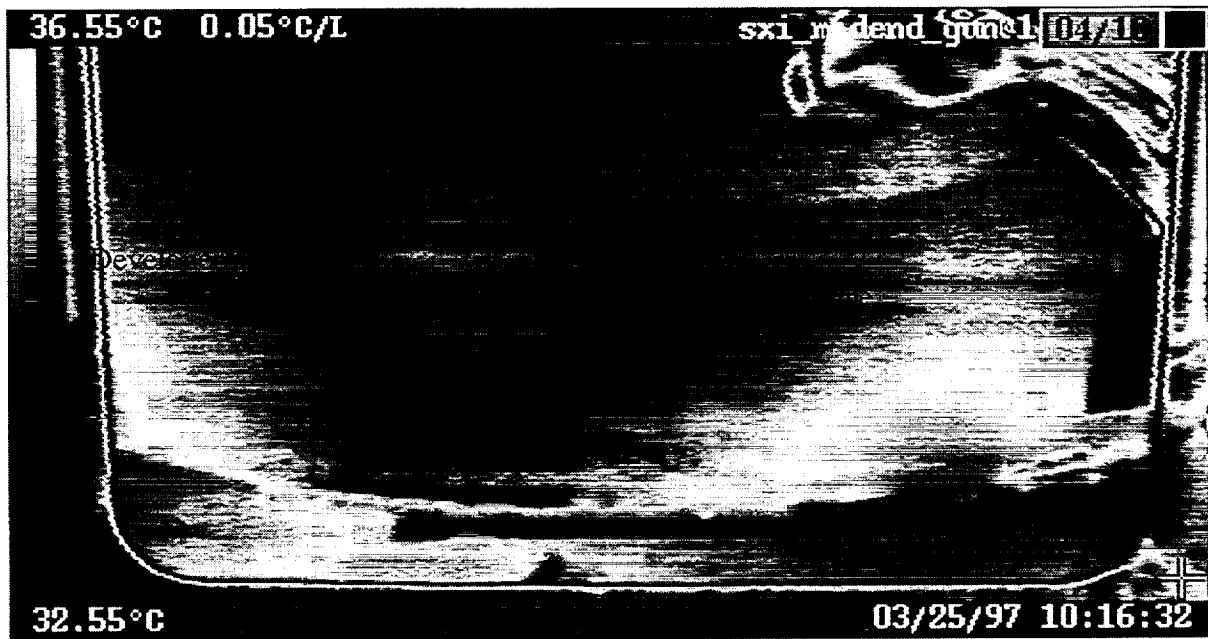




Top pad attach points (Flash heating)



Mid-attach point (Flash heating)



Mid-attach points (Heat gun)



Top pad attach points (Heat gun)



Pad 1 (Left side) (heat gun)



Pad 2 (Right) (Heat gun)

5.11 Thermography Of LH₂ Feedline Fairing For X-33

A graphite/epoxy LH₂ Feedline Fairing for the X-33 was inspected utilizing front “viewing” side flash heating from the Bales TIP. The power setting of the flash lamps was set to 1400v and the tube was imaged at a distance of 32 inches. The delay between frame acquisition was set to 20 msec. Frames 2 through 11 have been saved for archival purposes on laser disk.

The geometry of the tube required that the tube be imaged from 11 positions as shown in Figure XX. The intent of choosing the various positions was to provide maximum normal incidence coverage of the tube, while keeping the total number of images to a minimum.

The only defects located or identified was a grinding mark, approximately 0.5 inch square, on the inside of the tube. The mark appears to be almost all the way through the tube, but is not visible from the outside. No scheduled defects were planned for this component.

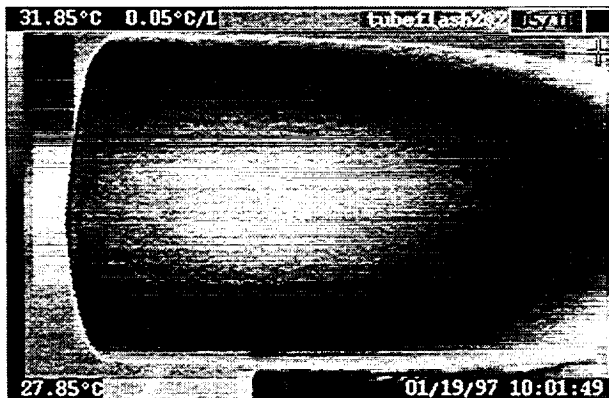
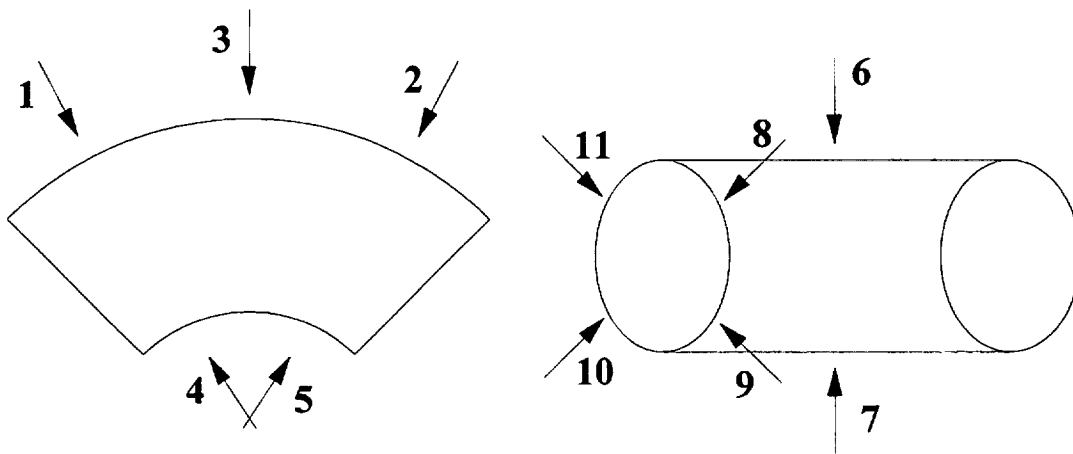


Image 2

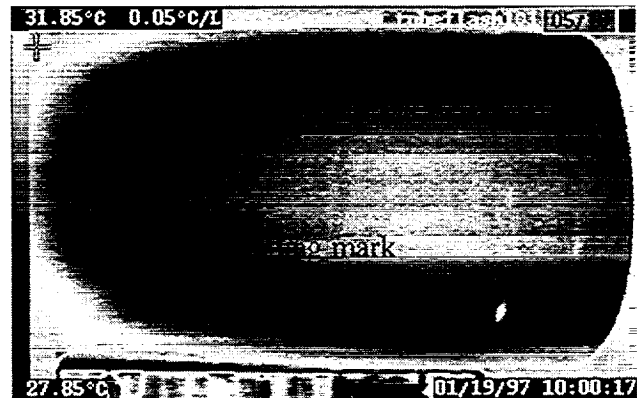


Image 1



Image 3

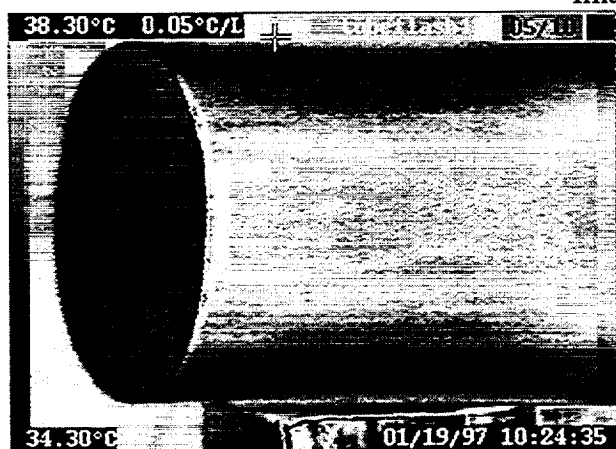


Image 4

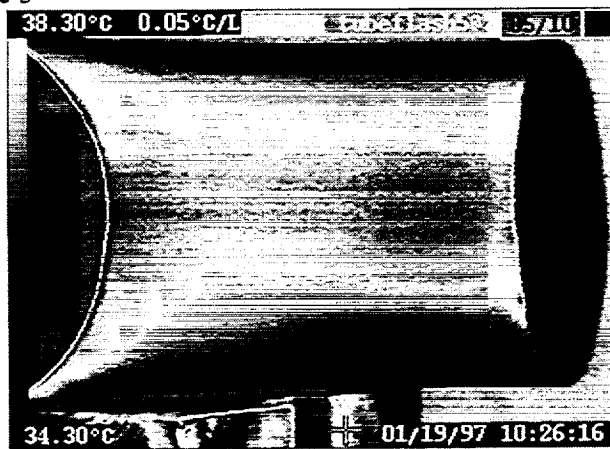


Image 5



Image 7

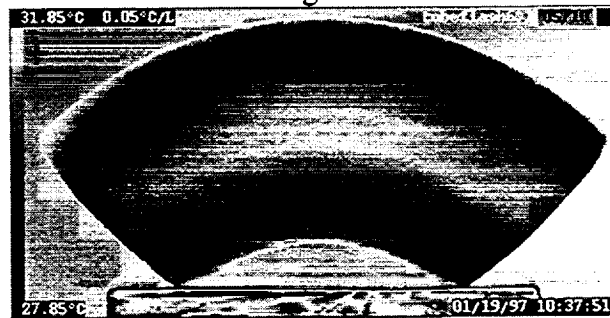


Image 6

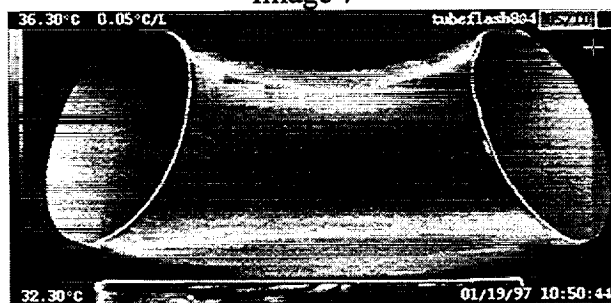


Image 8

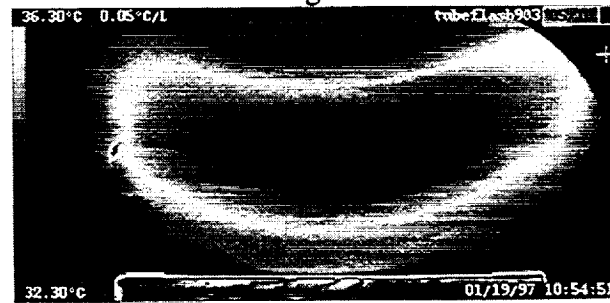


Image 9



Image 10

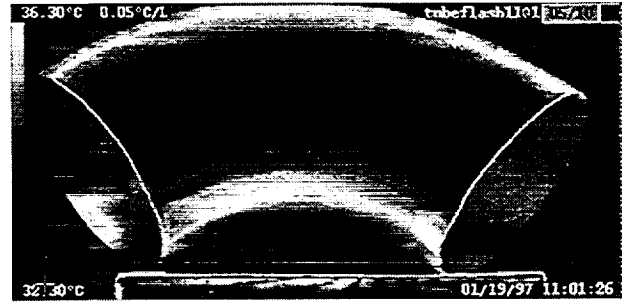
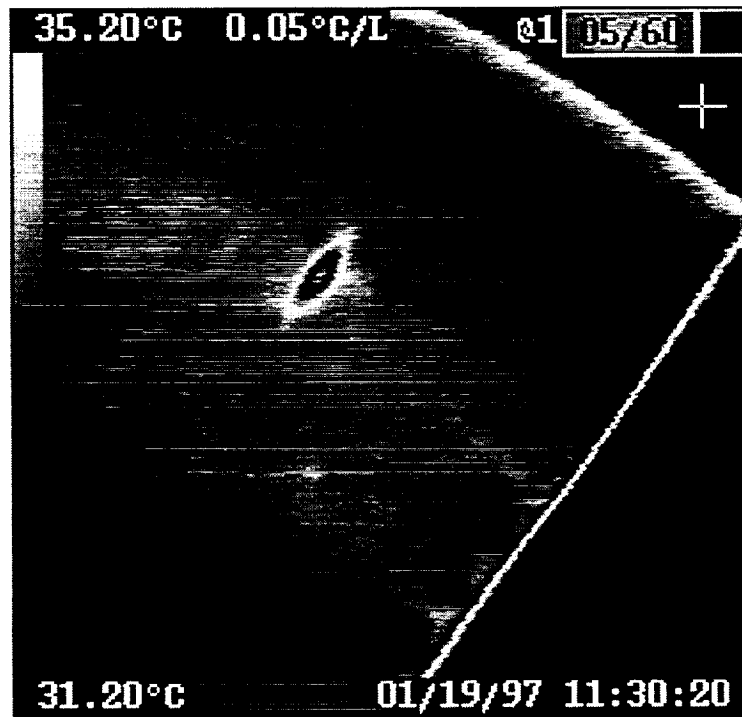


Image 11



Close-up image of tool mark

5.12 Thermography of Foam Core Sandwich Panel

A graphite/epoxy hot gas panel for developmental work on the SRB Nose Cone was tested prior to hot gas treatment. The panel was inspected utilizing the Bales TIP flash system set to a 1400v power setting and a 20 msec per frame delay.

Backside:

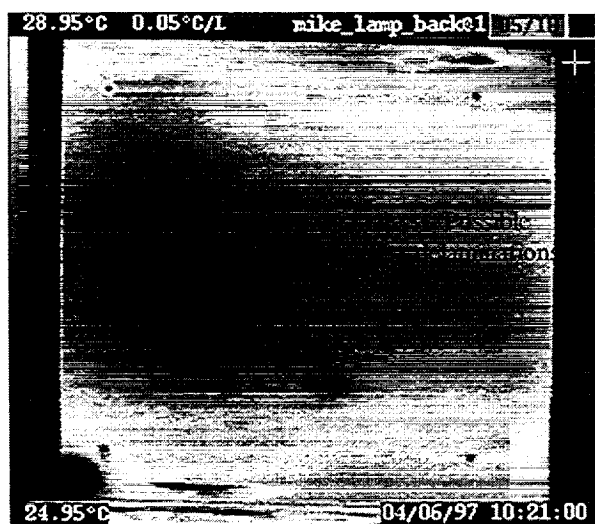
Two regions were found on the edge overlap that were disbanded. Over the entire acreage small thermal abnormalities were found. These abnormalities appear to be resin starved regions.

Frontside

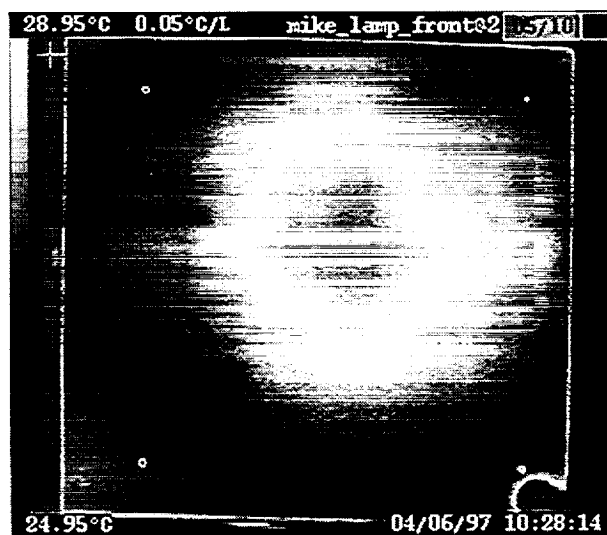
Each bolt hole shows some degree of damage. The upper right hand bolt hole appears to be in the worst shape, with delaminations running approximately 1/4 inch up and down the panel.

There also appears to be some form of subsurface feature below the visible surface wrinkle on the top of the panel. Without a reference standard it is difficult to tell if the thermal inspection is reaching the core/faceplate interface.

Inspection of the panel using through transmission long term heating (1000W IR heat lamp) yielded no additional defect status information to that of the pulse heating method.

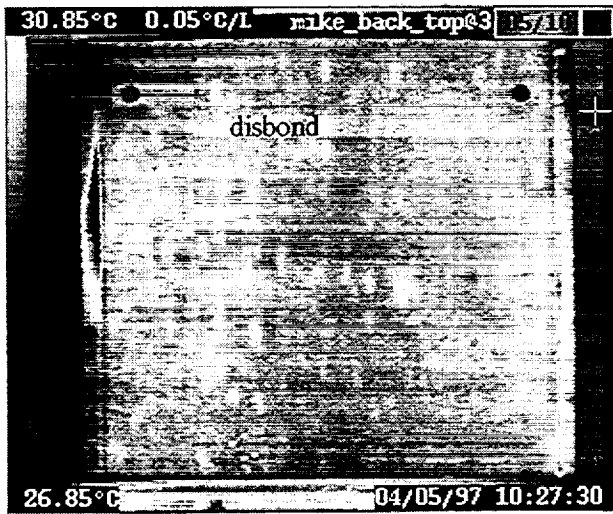


(5) Backside

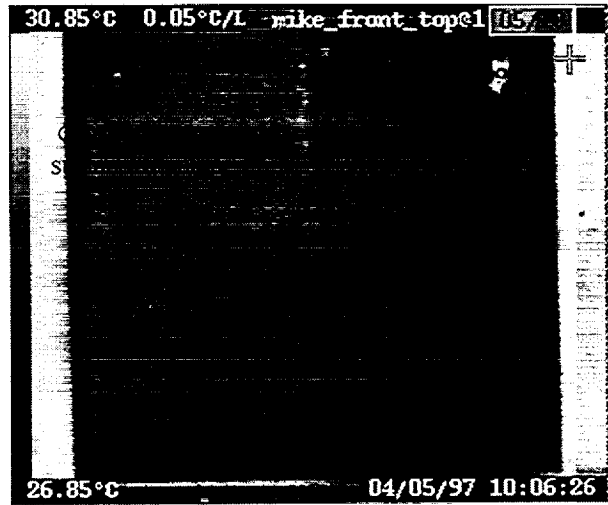


(6) Frontside

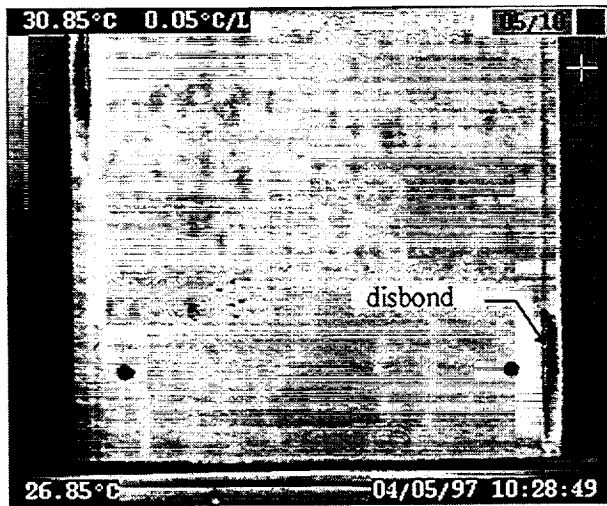
FRONTSIDE 1000W LAMP HEATING



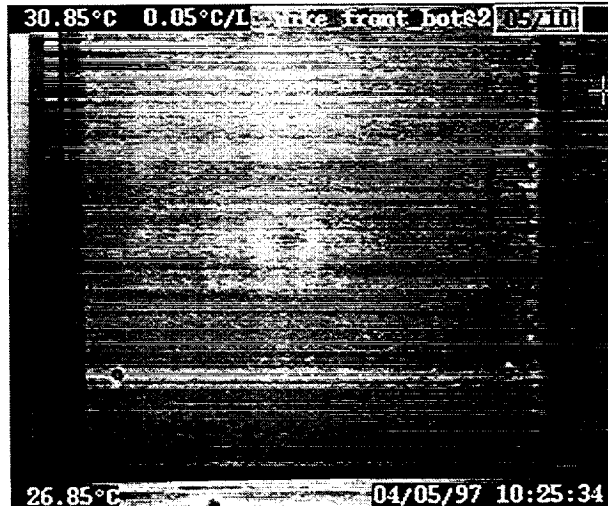
(1) Backside top



(2) Frontside top



(3) Backside bottom



(4) Frontside top

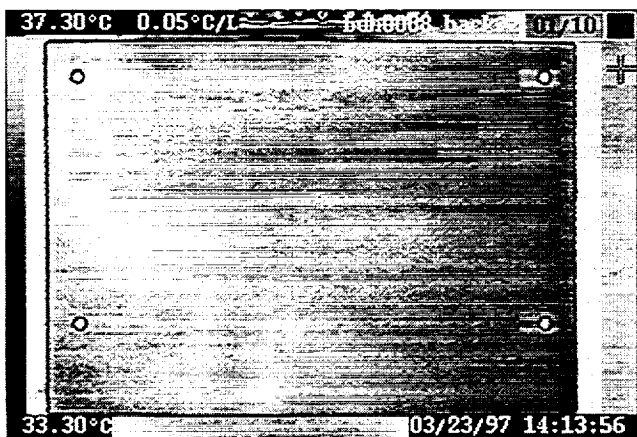
PULSE HEATING

12.13 Thermography of Hot Gas Panels For LO₂ Feedline Fairing

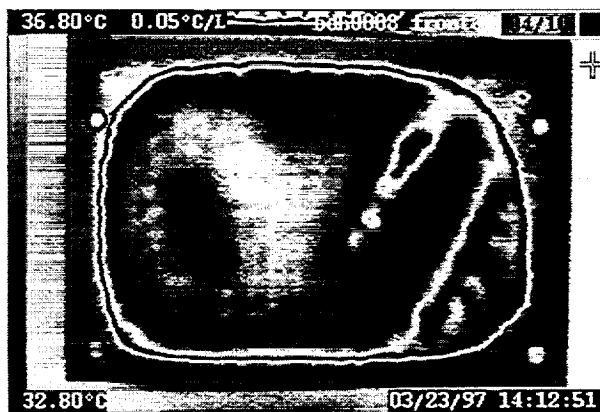
As part of the hot gas testing of the proposed composite LO₂ feedline fairing, four panels were inspected using thermographic NDE techniques. The 18 ply panels are made from a graphite cloth in a polyimide resin matrix. The panels were taken from the same lot used to fabricate a test article, one of two made by Marion Composites. One article fairing is undergoing qualification for flight at Marion, while the other fairing, whose material came from the lot that these panels were made from, is a test article shipped to MSFC for verification.

This program, part of the Shuttle Upgrade 2030 Project, has continued after a hiatus of a year. A concern when the program ended last year was the cause of certain delaminations and blisters that occurred just below the surface of these full-size layups during thermal dynamic testing. This condition was not prevalent on the flat panel specimen testing. A suggestion was made to find the reason for this. Was it volatile gases escaping from the edges? It was decided to tape the edges of the side of the panels with different compounds to see if this would cause similar conditions as that found on a full-size component where edge effects are not prevalent. One panel was sealed with a red silicon adhesive, while the other panel had a dark Havaflex Ceramic compound sealant. The objective was to perform hot gas testing on these panels and then measure the ΔP vapor pressure on the part and correlating that with other tests. It was expected that 80% of the volatiles consists solely of methanol.

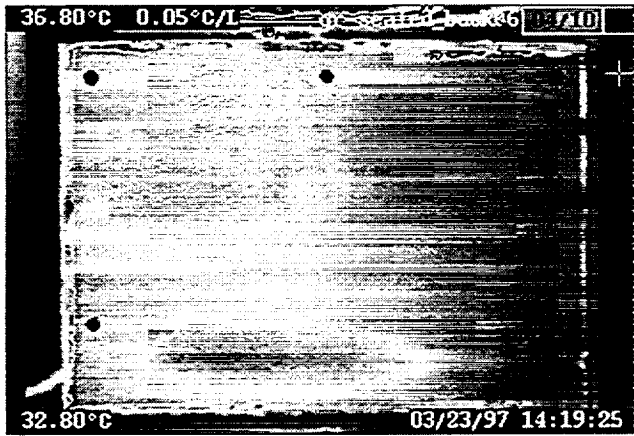
The panels were inspected utilizing the Bales TIP and flash heating. The system was configured with a power setting of 1400v, time delay of 20 msec per frame and image distance of 32 inches



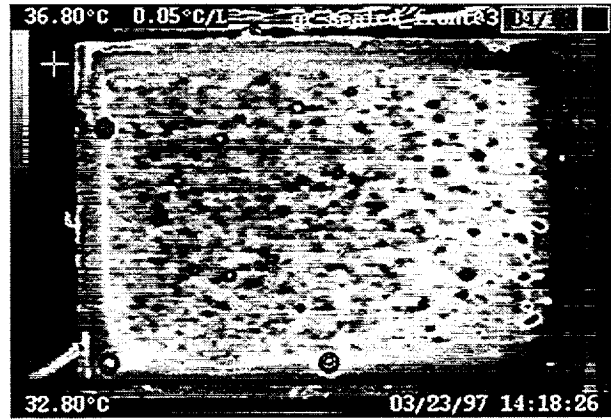
BDH0008 - Tool side



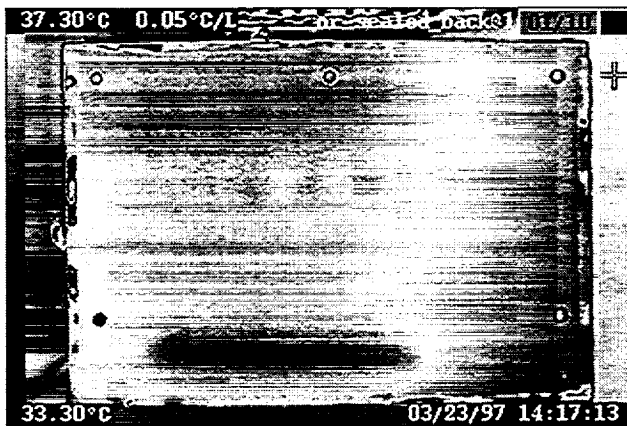
BDH0008 - Front



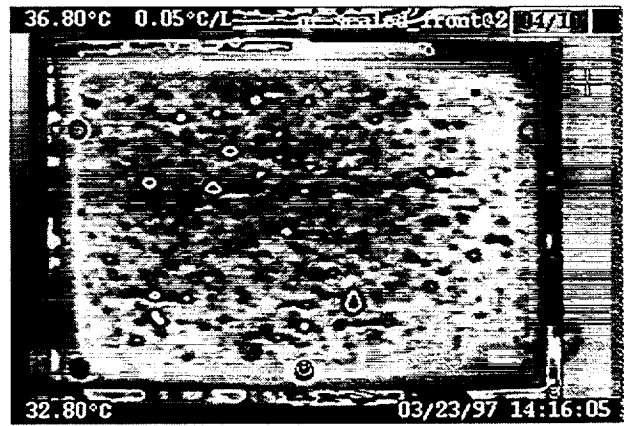
Gray sealant - Tool side



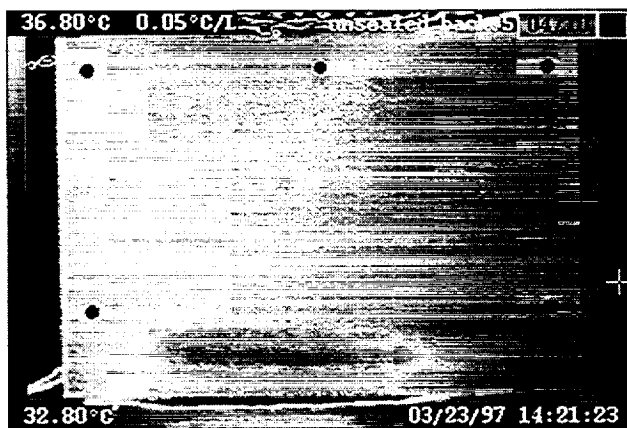
Gray sealant - Front



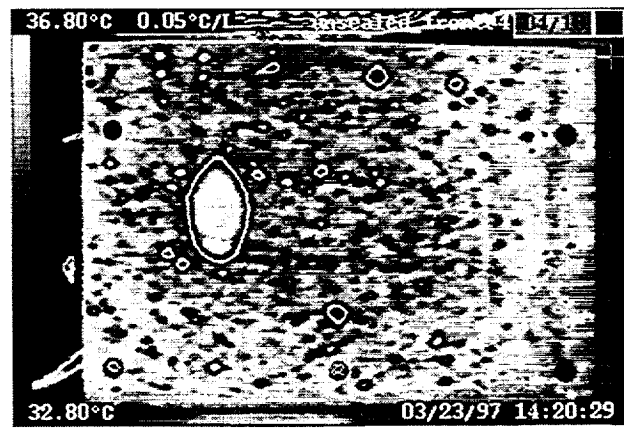
Orange sealant - Tool Side



Orange sealant - Front



Unsealed - Tool side

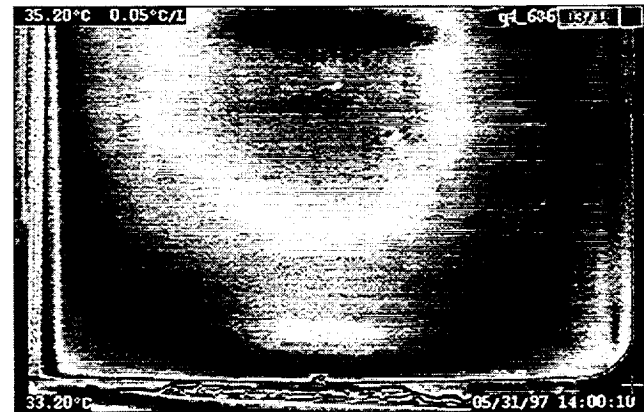
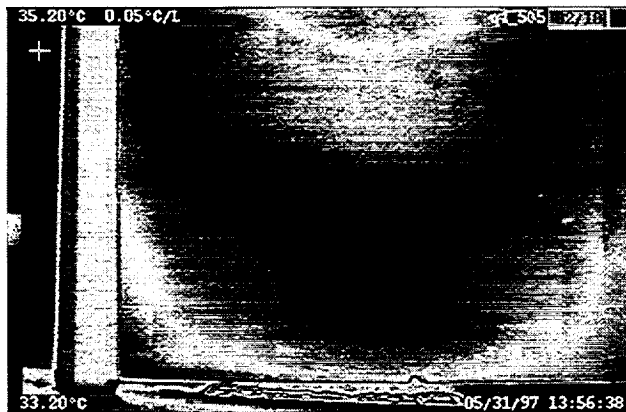
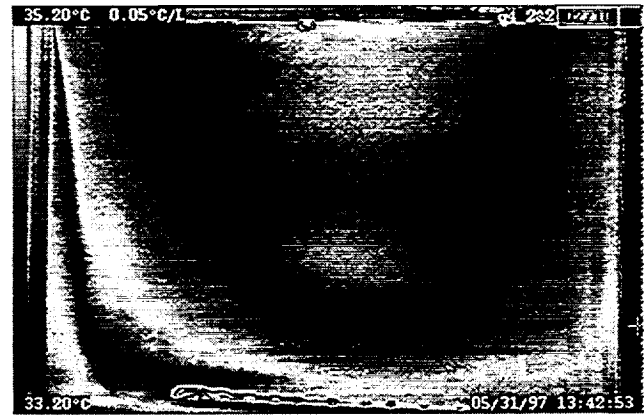
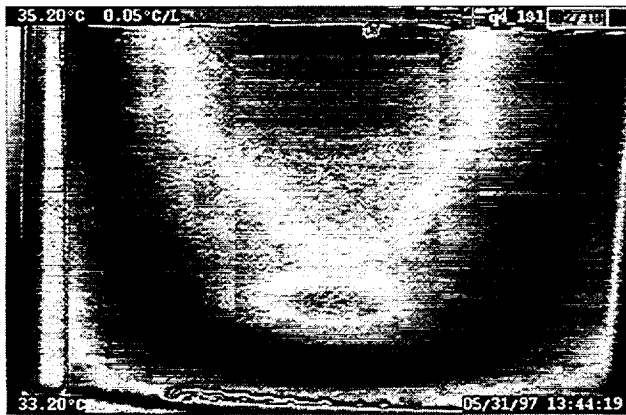


Unsealed - Front

5.14 Thermography Of Space Station Rack Rear Access Panel (Q4)

Configuration: Flash heating (Imaged at 32 inches, 1400V)

- Good correlation with porosity region detected by UT.
- Porosity not detectable from front surface scan of rack.



Close-up of porosity

6.0 CONCLUSIONS

Thermography has proven to be very useful for inspecting large composite aerospace structures. Defects including porosity, inclusions and delaminations were successfully located in a broad range of composite materials resulting from manufacturing and service related problems. Various procedures and methods for thermally exciting the composite structure were investigated. It was found that on "highly insulative" structures, such as those with thicknesses in excess of 0.25 inch or those with foam insulation, long term exposure to a high intensity heat lamp or hot air gun gave the best results. On thin structures, or those that transmitted heat more freely, a quick burst of heat from a flash unit worked best.

Several "rules-of-thumb" were established for the practical inspection of aerospace composites with regard to depth of penetration and flaw size. A practical inspection being one where a large, better than a foot square, region is covered in a single inspection; no surface preparation is applied or performed; no knowledge of the prior history of the part is given; critical flaw size is on the order of a quarter of an inch square.

First, for graphite epoxies with a dull surface finish, the practical inspection limit can be taken to be about 15 to 16 plies for inclusions, disbonds and porosity. This value drops to between 6 and 7 plies if the surface is shinny. For Kevlar/epoxies these values are slightly lower, and fall off drastically if mixed with foams. In graphite/phenolics, the practical inspection depth was found to be on the order of 1/16 of an inch. Carbon/silicon carbide structures were found to only be inspectable on their surfaces. Finally, metallic honeycomb structures were found to only be inspectable if a surface treatment of powdered developer was applied to dull the surface.

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16. Abstract <p>The purpose of this work is to develop thermographic inspection methods and standards for use in evaluating structural composites and aerospace hardware. Qualification techniques and calibration methods are investigated to standardize the thermographic method for use in the field. Along with the inspections of test standards structural hardware, support hardware is designed and fabricated to aid in the thermographic process. Also, a standard operating procedure is developed for performing inspections with the Bales Thermal Image Processor (TIP).</p> <p>Inspections are performed on a broad range of structural composites. These materials include various graphite/epoxies, graphite/cyanide-ester, graphite/silicon-carbide, graphite phenolic and Kevlar/epoxy. Also metal honeycomb (titanium and aluminum faceplates over an aluminum honeycomb core) structures are investigated. Various structural shapes are investigated and the thickness of the structures vary from as few as 3 plies to as many as 80 plies.</p> <p>Special emphasis is placed on characterizing defects in attachment holes and bondlines, in addition to those resulting from impact damage and the inclusion of foreign matter. Image processing through statistical analysis and digital filtering is investigated to enhance the quality and quantify the NDE thermal images when necessary.</p>					
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